FRONTIER KNOWLEDGE AND SCIENTIFIC PRODUCTION: EVIDENCE FROM THE COLLAPSE OF INTERNATIONAL SCIENCE

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Abstract

We show that WWI and the subsequent boycott against Central scientists severely interrupted international scientific cooperation. After 1914, citations to recent research from abroad decreased and paper titles became less similar (evaluated by Latent Semantic Analysis), suggesting a reduction in international knowledge flows. Reduced international scientific cooperation led to a decline in the production of basic science and its application in new technology. Specifically, we compare productivity changes for scientists who relied on frontier research from abroad, to changes for scientists who relied on frontier research from home. After 1914, scientists who relied on frontier research from abroad published fewer papers in top scientific journals, produced less Nobel Prize-nominated research, introduced fewer novel scientific words, and introduced fewer novel words that appeared in the text of subsequent patent grants. The productivity of scientists who relied on top 1% research declined twice as much as the productivity of scientists who relied on top 3% research. Furthermore, highly prolific scientists experienced the starkest absolute productivity declines. This suggests that access to the very best research is key for scientific and technological progress.

The creation of ideas is crucial for scientific progress, technological innovation, and economic development, particularly in a world where "knowledge has taken over much of the economy" (The

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Economist, 2000). As argued by many scholars (e.g. Arrow, 1962, Mokyr, 2002), one of the major inputs in the creation of new ideas is existing knowledge. Most famously, Isaac Newton acknowledged the importance of existing knowledge in his letter to Robert Hooke:

> "If I have seen further, it is by standing on ye shoulders of Giants." [Newton, 1675]

The quote not only emphasizes that scientists build on existing knowledge to produce new ideas, but also that knowledge produced by scientific "giants," i.e. frontier knowledge, is particularly important. Access to existing knowledge does not only fuel basic scientific progress but it is also key for the development of new technologies, as emphasized by theoretical models of economic growth (e.g. Romer, 1986, 1990; Jones, 1995; Weitzman, 1998).

In the first part of the paper, we document a sharp decline in international scientific cooperation around World War I (WWI). This decline severely reduced international citations in scientific papers, including citations to the international knowledge frontier. In the second part of the paper, we study how reduced access to the international knowledge frontier affected the production of basic science and its application in new technologies.

With the beginning of the war, the world split into the Allied (United Kingdom, France, later the United States, and a number of smaller countries) and Central (Germany, Austria-Hungary, Ottoman Empire, Bulgaria) camps. The involvement of scientists in the war effort and the extremely nationalistic stance taken by many scientists in support of their homeland, Germany in particular, pitted scientists in the two camps against each other. We document that the delivery of international journals was severely delayed and that international conferences were canceled or only involved scientists from one of the warring camps. Allied scientists were cut off from their peers in Central countries; in particular from Germany, a country whose scientists had received more than 40 percent of Nobel prizes in physics and chemistry in the pre-war period. Similarly, Central scientists were cut off from their peers in Allied countries; in particular from the United Kingdom (20 percent of Nobel prizes), France (15 percent of Nobel prizes), and the United States, the rising scientific superpower. This schism of the scientific world persisted during the post-war years because Allied scientists organized a boycott against Central scientists to punish them for their involvement in the war effort.

To quantify the decline in international scientific cooperation and to measure how it affected scientific progress, we collect data from various historical sources. First, we digitize more than 60,000 individual records from *Minerva – Handbuch der Gelehrten Welt*, the most comprehensive worldwide listing of university professors for this period, and we compile two censuses of all university scientists in the world for the years 1900 and 1914. Second, we collect data on all scientific publications, including references, in 160 top scientific journals for the period 1900 to 1930 from the *ISI Web of Science*. Third, we collect data on all Nobel Prize nominations for the years 1905 to 1945 from the Nobel archives. Fourth, we collect data on more than 2.5 million U.S. patents.

In the first part of the paper, we show that international citations in scientific papers severely declined during WWI and the subsequent boycott against Central scientists. After 1914, papers contained fewer citations to recent research from *outside* the camp, relative to research from home, i.e. Allied papers contained fewer citations to Central research, and Central papers contained fewer citations to Allied research. We estimate that the share of citations to research from outside the camp fell by 0.22, a decline of about 85 percent. We find a smaller decline in relative citations to foreign research from *inside* the camp, consistent with a smaller interruption of international scientific cooperation.

Moreover, we explore whether WWI and the boycott also affected citations to *top* research by focusing on references quoting research that ended up in the top percentiles of the citation distribution. After 1914, citations to top 5%, top 3%, and even top 1% research from outside the camp declined, relative to citations to corresponding top research from home.

The observed changes in international citations could be caused either by scientists not knowing about recent foreign research or by scientists deciding not to cite foreign research for political reasons. To distinguish between these two possibilities, we explore citations to pre-war research. In contrast to *recent* research, international citations to *pre-war* research did not fall disproportionately after 1914. This suggests that the observed changes in international citations were presumably caused by scientists not knowing about recent foreign research.

In further results, we analyze how the breakdown in international scientific cooperation affected the similarity of papers produced in the different camps. We use the machine-learning algorithm Latent Semantic Analysis (Deerwester et al., 1990; Landauer et al., 1998) to measure the similarity of paper titles. After 1914, the similarity to papers from outside the camp fell by 0.5 standard deviations relative to the similarity to papers from home. The similarity to papers from inside the camp did not fall significantly. These results suggest that the breakdown in international scientific cooperation also led to a divergence of research in the two camps.

In the second part of the paper, we study consequences of the decline in international scientific cooperation for the production of basic science and its application in new technologies. Specifically, we compare yearly productivity changes of scientists in field-country pairs that, in the pre-war period, relied on frontier research from abroad, e.g. biochemists in the United States, to scientists in field-country pairs that relied on frontier research from home, e.g. biologists in the United States. After 1914, scientists who relied on frontier research (as measured by the top 1%) from *outside* the camp, rather than from home, published significantly fewer papers. The results imply that U.S. biochemists published 0.1 standard deviations fewer papers per year after 1914, a productivity reduction of about 30 percent, compared to U.S. biologists. We also show that productivity declined for scientists in field-country pairs that relied on frontier research from *inside* the camp, but not significantly so.

Further results indicate that scientists who relied on top 1% research experienced productivity reductions that were at least twice as large as those of scientists who relied on top 3% or top 5% research. While researchers have always grasped the relevance of frontier research, our results emphasize the narrow-edged nature of the knowledge frontier.

We investigate whether the relative changes in productivity were most likely caused by a reduction in international knowledge flows, or by more general disruption during WWI. To control for disruption that affected all scientists to the same extent, all regressions include year fixed effects. Results remain unchanged if we control for camp-times-year, field-times-year, or camp-times-field-times-year fixed effects. These additional fixed effects control for war-related and other changes that differentially affected scientists in different camps (e.g. Allied scientists), fields (e.g. chemists), or fields within camps (e.g. Allied chemists). We also estimate regressions that include various measures of war intensity, such as the number of total or civilian deaths. To further probe whether WWI differentially affected death rates of scientists, we collect data on more than 6,500 obituaries published in contemporary scientific journals. In general, scientists in our sample did not die disproportionately during WWI. Moreover, we also show that scientists reliant on frontier research from abroad did not die disproportionately during this period. Additionally, we show that the results are robust to excluding chemists, who were most heavily involved in weapons development, and to considering only publications in home-camp journals, since publishing opportunities in foreign journals may have dwindled.

We also investigate effects on three alternative measures of scientific productivity: scientific breakthroughs, new scientific concepts, and new scientific concepts with technological applications. We find that scientists who relied heavily on frontier research from outside the camp, rather than from home, produced fewer scientific breakthroughs, as measured by research worthy of a Nobel Prize nomination.

We also study effects on new scientific concepts. Scientists who relied heavily on frontier research from outside the camp, rather than from home, produced fewer papers that introduced novel words, which serve as a measure of new scientific concepts. We define novel words as words that the scientist first used in a title of a paper published between 1905 and 1930 and that had not been used in any prior paper title. Examples of words that were introduced in this period are electroencephalogram, magnetron, hormone, isotope, and superconductor.

Furthermore, we study effects on the technological application of basic science. We develop a text-based method to establish a link from basic science to technology.[1] We search the full text of more than 2.5 million U.S. patents, containing 7.6 billion words, for the novel scientific words that

[1]Many scientific advances that affect the development of new technology are not formally cited in patents. E.g. U.S. patent nr. 3,699,947 "Electroencephalograph Monitoring Apparatus," granted in 1972, does not mention any scientific paper, not even those of Hans Berger who laid the scientific foundations of electroencephalography in the 1920s and 1930s. Our text-based method also allows us to measure effects on technology for a time period before the U.S. Patent Office introduced formal citations to basic science (in 1947).

scientists introduced in this period. For example, the novel scientific word "electroencephalogram" appeared seven times in subsequent patents and "magnetron" appeared 9,638 times. The measure captures connections between science and technology even if patents do not cite the relevant scientific papers. We find that scientists who relied heavily on frontier research from outside the camp, rather than from home, introduced fewer innovative words that found applications in patents.

Finally, we show that access to frontier research did not affect all scientists to the same extent. Output of above median productivity scientists decreased five to 15 times more, in absolute terms, than output of below median scientists. These results suggest a complementarity between access to frontier research and the underlying quality of scientists.

Our findings contribute to the literature on the effect of basic science on technological development, a link that is difficult to establish empirically. Our results indicate that access to frontier knowledge impacts the production of basic science that is applied in the development of new technology. Other research has shown that increased funding from the U.S. National Institutes of Health (NIH) for basic biomedical research increases patenting by private sector companies (Azoulay et al., 2016) and that NIH open access mandates increase citations to biomedical research by inventors (Bryan and Ozcan, 2016).[2]

Our findings emphasize that access to existing frontier research is particularly important for the creation of ideas and that high-quality scientists make greater use of it. Because the physical costs of gaining access to frontier research have fallen since the early 20th century, especially with the introduction of the Internet and improved transportation, the main cost of access today lies in discerning the knowledge frontier from the millions of scientific papers published every year. While not specifically investigating the role of frontier knowledge, previous literature has shown that access to existing knowledge affects follow-on research. For example, materials that have been deposited in biological resource centers, which collect and distribute biological material, are more likely to be used in follow-on research (Furman and Stern, 2011). Intellectual property rights increase the cost of using prior knowledge in follow-on research (Scotchmer, 1991; Williams, 2013; Murray et al., 2009; Galasso and Schankerman, 2015; Biasi and Moser, 2015). The compulsory licensing of German patents after WWI, for example, increased patenting by U.S. inventors in the 1930s (Moser and Voena, 2012).

Our results also contribute to the literature on the knowledge production function, by highlighting the importance of frontier knowledge. The existing literature has shown that papers that cite "atypical combinations" of references are more likely to become a "hit" (Uzzi et al., 2013; Wang et al., 2016), as are papers that predominantly cite recent as well as some older references (Mukher-

[2]Increased funding for universities and the establishment of technical universities increases patenting (Aghion et al., 2009; Toivanen and Väänänen, 2016). Earlier research shows that basic science is associated with private sector innovation, without taking advantage of plausibly exogenous variation in basic science (e.g. Jaffe, 1989; Acs et al., 1992; Mansfield, 1995; Adams, 1990). More broadly, universities are associated with faster growth (Valero and Van Reenen, 2016) and engineers are particularly important (Murphy et al., 1991).

jee et al., 2017). More generally, human capital is more important for scientific production than physical capital (Waldinger, 2016). Star scientists are key, because they affect the productivity of co-authors (Azoulay et al., 2010; Oettl, 2012; Borjas and Doran, 2015), attract other good scientists to their universities (Waldinger, 2016, Agrawal et al., 2017), attract researchers to promising research fields (Moser et al., 2014), and train PhD students (Waldinger, 2010).[3] With the stock of knowledge constantly increasing, scientists must absorb ever more information to reach the knowledge frontier and, therefore, they must invest more time in training and collaborate in larger teams (Jones, 2009, Wuchty et al., 2007).

The results also speak to the literature on international knowledge flows by showing that political events can disrupt international knowledge flows and lower scientific productivity. Previous research has shown that city, state, and country borders are important barriers to knowledge flows, as measured by patent citations (e.g. Jaffe et al., 1993; Thompson and Fox-Kean, 2005; Peri, 2005; Belenzon and Schankerman, 2013; Head et al., 2015). Reductions in travel costs boost collaborations of scientists in different cities (Catalini et al., 2016). Western-to-Communist book translations were rare during the Cold-War period, but increased substantially after the collapse of the Soviet Union (Abramitzky and Sin, 2014).

1 A Shock to International Scientific Cooperation

1.1 Brief History of Science Around WWI

Science became increasingly international during the second half of the 19th century, particularly in the years leading up to WWI—the so-called "golden age of internationalism" in science (Crawford, 1988). Scientists published their most important contributions in international journals, conferences became more international, and scientific societies increased international cooperation. In 1899, leading nations founded the *International Association of Academies* to "facilitate scientific intercourse between the different countries" (Greenaway, 1996). To improve access to international research, the Royal Society, the oldest scientific society in the world, coordinated the publication of the *International Catalogue of Scientific Literature,* which translated the titles of virtually all scientific papers into English, German, French, and Italian.

The increasing internationalization of science was abruptly interrupted by the outbreak of WWI, at the end of July, 1914. The Western world split into two warring camps with the Allies (UK, France, later the United States, and a number of smaller countries) fighting the Central Powers (Germany, Austria, Hungary, the Ottoman Empire, and Bulgaria) (see Table I). While the war caused millions of military deaths, it caused relatively few civilian casualties in the major scientific powers (USA [757

[3] Other research has shown negative effects of stars when journal and faculty slots are fixed (Borjas and Doran, 2012). Similarly, star scientists do not seem to have a positive effect on their peers in the same department (Waldinger, 2012; Agrawal et al., 2017; Borjas and Doran, 2015).

deaths], UK [16,829, mostly merchant fleet], and Germany [720]), because the war was not fought on the territories of these countries.

All major war participants enlisted some of the most prominent scientists to support the war effort, particularly for the development of chemical weapons. The German unit was led by future Nobel Laureate Fritz Haber, who assembled a team of prominent chemists to develop new poisonous gases. His team included seven future Nobel Laureates: James Franck, Gustav Hertz, Otto Hahn, Walter Nernst, Emil Fischer, Heinrich Wieland, and Richard Willstätter (Van der Kloot, 2004). The French unit was led by Victor Grignard, who had received the Nobel Prize in 1912. The U.S. unit also enlisted prominent scientists, including the future president of Harvard, James Bryant Conant.

During this period, many scientists, particularly those from Germany, took a nationalistic stance and even issued statements in support of their home country's military actions. In the infamous *Manifesto of the 93*, which was widely published in October 1914, 93 German intellectuals, among them 14 science Nobel Laureates, declared their support for Germany's military actions, the killing of Belgian civilians, and the destruction of Leuven with its famous university library. Two weeks later, 3,000 German university teachers endorsed a declaration that "…Europe's culture depends on the victory of the German military" (Reinbothe, 2006, p. 99). In a reply that was published in *Nature*, the British chemist and Nobel Laureate William Ramsay condemned German scientists stating that "their ideal…is to secure world supremacy for their race…" (Ramsay, 1914).

The participation in the war effort and the hostile attitude toward their international peers soured international scientific relations. As early as October, 1914, William Ramsay had suggested "restrictions of the Teutons" (Ramsay, 1914) for the post-war era. Just before the end of the war, Allied scientists organized a conference that paved the way for a boycott against Central scientists. The scientists announced that

> "…the Allied Nations are forced to declare that they will not be able to resume personal relations in scientific matters with their enemies until the Central Powers can be readmitted into the concert of civilized nations." [Quoted in Lehto, 1998, p. 18.]

At a follow-up conference, over 200 scientists from 12 Allied countries founded the International Research Council (IRC) to organize post-war international scientific cooperation.[4] The IRC ensured that scientists from Central countries were effectively cut-off from Allied scientific associations and international scientific meetings, even if the associations or conference organizers were not officially affiliated with the IRC (Schroeder-Gudehus, 1973). While the boycott was strictly enforced in the first post-war years, its strength declined over time. In 1922, the Allied majority rejected a proposal by Neutral scientists to invite Central scientists to join the IRC (Cock, 1983, Lehto, 1998, p. 38). In the following years, the Allied position softened and the boycott was officially terminated in June

[4]The IRC replaced the *International Association of Academies* that had overseen international scientific relations in the pre-war era. The IRC statutes explicitly excluded former Central countries, but some formerly Neutral countries were invited to join as members (Kevles, 1971, p. 58).

1926 (Lehto, 1998, p. 40).[5] Two years later, the eminent German mathematician David Hilbert was honored to deliver the opening address of the International Congress of Mathematicians in Bologna. He proclaimed:

> "It makes me very happy that after a long, hard time all the mathematicians of the world are represented here. This is as it should be and as it must be for the prosperity of our beloved science...For mathematics, the whole cultural world is a single country."
> [Quoted in Reid, 1970, p. 188.]

1.2 Delivery of International Journals and Attendance of Conferences

During the war and the subsequent boycott both Allies and Centrals became increasingly strict about sharing scientific knowledge with foreign countries. Access to foreign journals became restricted and most international conferences were canceled during the war. Central scientists were banned from attending international conferences during the post-war boycott. More generally, most efforts to foster international scientific cooperation were interrupted during this period. The publication of the *International Catalog of Scientific Literature*, for example, was discontinued after 1914.

Access to Scientific Journals from Foreign Countries

We measure how the war and the boycott reduced access to foreign journals by investigating entry stamps from the Harvard library. To register the delivery of a journal, Harvard librarians placed an entry stamp on each issue upon arrival (see Appendix Figure A.1 for an example). We collect data on these stamps for the years 1910, 1913, 1917, 1919, 1921, 1923, and 1927 for four international journals: the *Zeitschrift für Analytische Chemie*, the *Annalen der Physik*, *Comptes Rendus Hebdomadaires des Séances de l'Académie des Sciences*, and *Nature*. We then calculate the average delay between the publication of a journal and its arrival at Harvard (see Data Appendix E.1 for details).

Before the war, the German *Zeitschrift für Analytische Chemie* arrived with a delay of about 26 days (Figure I, panel a). By 1917, the delay increased to about 500 days, or nearly one and a half years. In 1919, deliveries improved but the delay remained lengthy, close to 150 days. Between 1921 and 1923, the delay was still 100 days. By 1927, the journal was delivered almost as quickly as in the pre-war period. The pattern for the *Annalen der Physik*, the German journal that published Albert Einstein's famous 1905 papers, looks similar (Figure I, panel a).

We also plot delays for two Allied journals from abroad, the French journal, *Comptes Rendus*, and the British journal, *Nature*, the leading general scientific journals from these countries. Before the war, the *Comptes Rendus* arrived about 21 days after publication (Figure I, panel b). By 1917, the delay increased to about 45 days. By 1919, the delay extended to 57 days, about three times longer

[5] In June 1926, Germany, Austria, Hungary, and Bulgaria were invited to join the IRC. While the German scientific academies officially declined the invitation, the boycott was effectively terminated at this point.

than in the pre-war period. After 1921, the delay returned to its pre-war level. Before the war, *Nature* arrived only 10 days after publication – faster than the other journals, presumably because of shorter shipping routes from Britain. The delay for *Nature* almost tripled to 27 days during the war, and then partly recovered to about 19 days by 1921.

While the arrival delay for all foreign journals increased during the war and the boycott, the delay for German journals increased markedly more than for Allied journals (Figure I, panel c). To investigate whether the increase in arrival delays for German journals was caused by a general disruption of the German publishers, we compare arrival delays for the *Annalen der Physik* at Harvard and the German University of Heidelberg (see Data Appendix E.1 for details). Even at Heidelberg, the delay increased during the war, but nowhere near as much as at Harvard (Figure I, panel d).

These patterns indicate that foreign journals, in particularly those from the enemy camp, became harder to access during the war and the boycott. Moreover, since Harvard has one of the best-funded university libraries in the world, it is plausible that the delays experienced by other universities were more extensive.

Scientific Conferences

The war and the boycott also impacted international scientific conferences. In the pre-war period (1900-1914), scientists held 443 large international congresses. During the war (1914-1918), only seven international congresses took place (Forschungen und Fortschritte, 1933). In the post-war period, the number of international congresses was less than 20 in 1919, but steadily increased to 110 in 1926, and to 165 in 1930 (Kerkhof, 1940).[6] During the boycott, Central scientists were banned from most international conferences. While this ban was strictly enforced in the first post-war years, it continued to limit conference attendance of Central scientists until 1926. Kerkhof (1940) reports that the ban on German scientists applied to all international conferences in 1919; to about 85 percent in 1920; to about 60 percent in 1921 and 1922; and to about 50 percent in 1924 and 1925. After 1926, German scientists were excluded from fewer than 15 percent of international conferences.

We complement the historical accounts with data on attendance records of the *International Congress of Mathematicians* (ICM), the largest mathematics conference. In the pre-war period, Germany always sent large delegations to the ICM (see Table II, column 1). The 1916 congress that was scheduled to be held in Stockholm was canceled because of the war. The first post-war congress in 1920 was not held in Stockholm, but was relocated to Strasbourg in a symbolic move. Strasbourg lies in the Alsace region that had been annexed by Germany in the 1870/71 war with France and was returned after WWI. German mathematicians were neither invited to Strasbourg (1920 congress), nor to Toronto (1924 congress). By 1928, the boycott had ended, and Germany sent the second largest delegation, after the host nation, to Bologna.

[6]These figures only refer to large international congresses, such as the *International Congresses of Mathematicians* below, and not to smaller international workshops. We are not aware of systematic data for the smaller gatherings.

We further document that even small and very elitist conferences were affected by the war and the boycott. We analyze attendance patterns at the *Solvay Conferences* in Physics. The Nobel laureate Werner Heisenberg lauded "[t]he Solvay meetings...as an example of how much well planned and well organized conferences can contribute to the progress of science" (Mehra, 1975, p. VII). The first *Solvay Conference* was organized in 1911 and was attended by the leading physicists of the time, including Marie Curie, Ernest Rutherford, Max Planck, and Albert Einstein (Figure II, panel (a) and Appendix Table A.2). In that year, nine of the 24 participants came from Central countries. In 1913, nine of the 31 participants came from Central countries. During the war, the *Solvay Conferences* were discontinued. The first post-war conference took place in 1921. Scientists from Central countries were not invited.[7] Nor were they invited to the 1924 conference. By 1927, the boycott had ended and five of the 30 participants came from Central countries.[8] The 1927 conference is possibly the most famous scientific conference ever organized. It took place at the height of the quantum revolution, and 17 of the 30 participants were current or future Nobel Laureates. In 1930, six of the 36 participants came from Central countries.

2 Data

2.1 Censuses of University Scientists for 1900 and 1914

We obtain data from various sources. First, we collect two historical censuses of all university scientists in the world for the years 1900 and 1914. The data come from two volumes of *Minerva – Handbuch der Gelehrten Welt*, the most comprehensive world-wide listing of university professors for this period. We digitize more than 2,500 pages that list university professors of all ranks (e.g. assistant, associate, and full professors), of all fields, and from all universities in the world (see Appendix Figure A.2 for a sample page).

The data contain information on 569 universities in the year 1900, and 973 universities in the year 1914 (Table A.1, panel A). Across all fields, we manually digitize the names, affiliations, and fields of 23,917 professors in 1900, and 36,777 professors in 1914 (Appendix Table A.1, panel A). Figure A.3 shows the distribution of scientists in 1914. The map illustrates the concentration of scientific activity in the United States and Western Europe.

We focus our empirical analysis on five scientific fields: medicine, biology, chemistry, physics, and mathematics. We concentrate on these because at that time scientists in these fields already

[7] The lone German invited to the 1921 and 1924 conferences was Albert Einstein, then a professor at the University of Berlin. The invitations reflected his special status in the scientific community and his reputation as an avid internationalist. He declined to attend in 1921 for personal reasons, and in 1924 because none of his German colleagues had been invited (Mehra, 1975, p. XXIII).

[8] Two more participants were de facto in the German system but are classified as Neutrals in Mehra's data. Heisenberg had a joint appointment at the German University of Göttingen and the Danish University of Copenhagen and accepted a professorship at the German University of Leipzig in 1927. Schrödinger moved to the University of Berlin in 1927.

established a habit of publishing the majority of their research in scientific journals.[9] Our data contain information on 10,133 scientists in 1900 and 15,891 scientists in 1914 across the five fields (Appendix Table A.1, panel B).

2.2 Publication and Citation Data

We also collect all papers that were published in 160 top scientific journals from the *ISI Web of Science* for the period 1900 to 1930 (see Appendix E.4.2 for details on the selection of journals and Appendix Table A.3 for a list of the 160 journals), including information on the cited references (see Appendix E.4.3 for a detailed description of how we obtain the full list of authors and citations for all cited references). The publishing process closely resembled publishing in modern times.[10]

The analysis crucially depends on knowing the country of authors and cited references. Most historical scientific journals, however, did not report author affiliations. For example, Max Planck's famous 1901 paper "On the Law of Distribution of Energy in the Normal Spectrum," which laid the foundation for the quantum revolution, did not include Planck's affiliation.

We assign countries to authors and references in a three-step, hierarchical process (see Appendix E.4.4 for further details). First, we use the country information from the affiliation reported in those papers that list affiliations. Second, we use the country information from the two scientist censuses.[11] Third, we expand the country information for authors with identical names within the corresponding citing or cited journal. Consider the example of Nobel Laureate Arthur Compton. "A. Compton" published a paper in the *Physical Review* in 1923 with a U.S. affiliation, and another paper in the *same journal* in 1920. Because the 1920 paper did not report an affiliation, we use the affiliation information from the 1923 paper to assign a U.S. affiliation to the 1920 paper.

We use the fraction of citing authors and referenced authors from each country to assign countries to papers and their references. A paper (or reference) exclusively written by authors from the United States, for example, counts as one U.S. paper. A paper co-authored by one U.S. author and one U.K. author, counts as 0.5 U.S. papers and 0.5 U.K. papers.[12]

[9] *Minerva* lists the exact specialization for each scientist. Many mathematicians, for example, do not report "mathematics" but "algebra" or "analysis," often in native languages, as their field. We manually re-code several thousands of the exact specializations into 32 fields (e.g. biology, physics, history, law, and so on).

[10] Because the historical part of the *Web of Science* focuses on the highest cited journals, it has very good coverage of Anglo-Saxon and German journals. The coverage of French journals, for example, is less comprehensive. This does not bias our analysis because our regressions implicitly control for persistent differences in coverage across countries.

[11] In the very rare cases that two or more scientists had identical names and worked in the same field but in different countries, we assign the paper proportionally to each country. For example, the censuses contain two chemists with the name J. Schmidt, one in Germany and one in Austria. We therefore count chemistry papers published by J. Schmidt as half German and half Austrian. Note that the *Web of Science* only reports the last name and initials of each author.

[12] The country of papers and scientists is assigned using the scientist's university affiliation. Between 1900 and 1914, 2.75 percent of scientists in Allied and Central countries moved across countries and 1.11 percent moved across camps. For papers in journals that report affiliations, the moves are reflected in our data. For papers that do not report affiliations, moves after 1914 will not be recorded and authors will remain assigned to the country where they worked in 1914.

Mistaking an author for another author with the same name from the same country does not introduce measurement error because the sole purpose of this matching is the assignment of countries to citing authors and referenced authors. Remaining mistakes in assigning countries to papers and references will introduce measurement error. Depending on the estimated specification, the measurement error will either affect the dependent variable or the explanatory variables. With classical measurement error, our results remain unbiased in the first case, and will be biased towards zero in the second case. The latter would make it more difficult to find significant effects.

2.3 Data on Nobel Prize Nominations

To measure scientific breakthroughs, we also collect data on nominations for the physics, chemistry, and physiology/medicine Nobel Prizes from Nobelprize.org (2014). The data contain 993 individuals who received at least one nomination for a Nobel Prize between 1905 and 1945. We merge these data with the publication data from the *Web of Science* to identify research that was worthy of a Nobel Prize nomination (see section 4.2.1 for details).

2.4 Full Text of U.S. Patents between 1920 and 1979

To assess how basic science produced in this period was applied in the development of new technology we obtain the full text of more than 2.5 million U.S. patents for the years 1920 to 1979 from the United States Patent Office (see appendix E.4.6 for details). The 2.5 million patents contain more than 7.5 billion words. We then search these data for novel words that were introduced by scientific papers between 1905 and 1930.

2.5 Final Datasets

We combine these data to construct two datasets: a paper-level dataset that allows us to study changes in international citations and the similarity of papers (in section 3), and a scientist-level dataset that allows us to study how the breakdown of international scientific cooperation affected the productivity of scientists (in section 4).

The paper-level dataset covers the period 1905 to 1930, and contains all papers for which we match the country of at least one author and at least one reference, and for which the Web of Science reports the number of times the references are cited until today.

The scientist-level dataset is a panel dataset of all university scientists who published at least one paper between 1905 and 1930. It contains yearly productivity measures for each scientist.

3 International Citations and the Similarity of Papers

We use the paper-level data to quantify how WWI and the boycott impacted references in scientific papers and the similarity of paper titles. These measures are attempts to proxy for international knowledge flows. Directly measuring knowledge flows between all scientists in the world would be nearly impossible. For example, one could not know or quantify whether scientists were aware of certain papers or whether they had *engaged* in discussion about specific research topics in formal or informal scientific gatherings with their colleagues.

3.1 The Effect of WWI and the Boycott on International Citations

First, we measure changes to international citations in scientific papers. For each paper, we count references as follows: to existing research from home, to foreign research from inside the camp, or to foreign research from outside the camp.[13] We divide these counts by the total number of references and obtain three shares: the share of citations to home ($\frac{c_{Home}}{C_{Total}}$), foreign countries inside the camp ($\frac{c_{Foreign-IN}}{C_{Total}}$), and foreign countries outside the camp ($\frac{c_{Foreign-OUT}}{C_{Total}}$).

To measure citations to *recent* research, we consider references to research published in the preceding five years.[14] The average paper in our sample includes 17.6 references overall; of these, 7.4 cite recent research, and 4.6 cite recent research published in one of the 160 journals in our data. Out of these 4.6 references, we are able to match the country to 3.0 references. For 2.6 of these references, the *Web of Science* reports the number of times the reference had been cited until today.

Figure (III) illustrates our measure. A paper published by a U.S. author in year t includes four references to research published in the preceding five years; one reference to U.S. research that was published in year t, one reference to German research that was published in year t, one reference to U.K. research that was published in year $t-2$, and one reference to U.S. research that was published in year $t-4$. The corresponding shares are:

$$\frac{c_{Home}}{C_{Total}} = \frac{2}{4} = 0.5, \qquad \frac{c_{Foreign-IN}}{C_{Total}} = \frac{1}{4} = 0.25, \quad \text{and} \quad \frac{c_{Foreign-OUT}}{C_{Total}} = \frac{1}{4} = 0.25.$$

Table III summarizes the citation shares in our sample. About 69 percent of references quote research from home, 16 percent quote research from foreign authors inside the camp (e.g. U.S. papers quoting research from the United Kingdom), and about 15 percent quote research from outside the camp (e.g. U.S. papers quoting research from Germany). If we consider citations to the very best research, as measured by references that quote research that ended up in the top 1% of the citation distribution, 5.4 percent of references quote top research from home, 1.2 percent quote top research from foreign authors inside the camp, and about 1.3 percent quote top research from outside the camp.

[13]For the main results, we exclude self-citations when we count the references to research from home. The results are robust to including self-citations as citations to research from home (see Appendix Table A.7)

[14]The results are robust to considering research published in the preceding three or ten years as recent research (see Appendix Table A.8)

Citations to All Research

We create three observations per paper: the share of references quoting research from home, from inside the camp, and from outside the camp. We then investigate how these shares changed after 1914 by estimating the following regression:

$$\begin{aligned}
Citation\ Shares_{ic} &= \omega_1 \cdot 1\left[c = \text{Foreign Out}\right] + \omega_2 \cdot 1\left[c = \text{Foreign Out}\right] \times 1\left[t\left(i\right) = \text{Post 1914}\right] \\
&+ \iota_1 \cdot 1\left[c = \text{Foreign In}\right] + \iota_2 \cdot 1\left[c = \text{Foreign In}\right] \times 1\left[t\left(i\right) = \text{Post 1914}\right] \qquad (1) \\
&+ \text{Citing Paper}FE_i + \epsilon_{ic},
\end{aligned}$$

where *i* indexes citing papers and *c* indexes camps. A home indicator is excluded from the regression. Hence, ω_1 measures how the pre-war share of references to research from outside the camp differed from the pre-war share of references to research from home. Similarly, ι_1 measures how the pre-war share of references to research produced by foreign authors from inside the camp differed from the pre-war share from home. The parameters of interest, ω_2 and ι_2, measure how the foreign shares changed after 1914, relative to the home share.

The regression also includes a fixed effect for each citing paper. These fixed effects control for changes in citation patterns over time because the sum of all paper fixed effects within a year are collinear with a year fixed effect. Similarly, the fixed effects control for permanent differences in citation patterns across countries, e.g. if U.S. authors generally include more references to research produced at home (a U.S. fixed effect, for example, would be collinear with the sum of paper fixed effects for all U.S. papers). The paper fixed effects also control for permanent differences in citation patterns across fields, e.g. if chemists always cite more research produced at home because the chemical industry is differently specialized across countries. The fixed effects also control for permanent differences across fields in a certain country, e.g. if U.S. chemists generally cite more research produced at home. To account for a potential correlation of standard errors in a certain field-country pair, e.g. chemistry in the United States, we cluster standard errors at the field-country level.

After the onset of WWI, papers cited relatively less research from *outside* the camp. The share of references quoting research from outside the camp fell by 0.22, relative to the home share (Table IV, column 1, significant at the 1 percent level), a reduction of 85 percent relative to the pre-war share of references quoting research from outside the camp. The share of references quoting research from foreign authors *inside* the camp fell by 0.07, relative to the home share (Table IV, column 1, significant at the 10 percent level), a reduction of 50 percent relative to the pre-war share of references quoting research from inside the camp. The decline in the share of references quoting research from outside the camp was significantly larger than the relative decline in the share of references quoting research from inside the camp (p-value $<$ 0.001). The results for both camps are slightly larger, in absolute magnitude, if we include camp-specific linear trends in the regression (Table IV, column 2).

The estimated effect varies over time. The relative decline of the share of references quoting research from outside the camp was 0.22 during WWI, 0.25 during the boycott, and 0.19 in the post-boycott period (Table IV, column 3, all significant at the 1 percent level).[15] The relative decline in the share of references quoting foreign research from inside the camp was 0.11 during WWI, 0.09 during the boycott, and 0.05 in the post-boycott period (Table IV, column 3, only the first two are significant at the 1 percent and 5 percent level, respectively). The results are slightly larger if we control for camp-specific linear trends (Table IV, column 4).

To get a better understanding of the timing of these changes, we estimate yearly coefficients:

$$\begin{aligned} \mathit{Citation\ Shares}_{ic} &= \sum_{\tau=1905}^{1930} \omega_\tau \cdot 1\left[c = \text{Foreign Out}\right] \times 1\left[t\left(i\right) = \tau\right] \\ &+ \sum_{\tau=1905}^{1930} \iota_\tau \cdot 1\left[c = \text{Foreign In}\right] \times 1\left[t\left(i\right) = \tau\right] \\ &+ \text{Citing Paper}FE_i + \epsilon_{ic}. \end{aligned} \tag{2}$$

A home indicator is excluded from the regression. Hence, ω_τ measures how the share of references to research from outside the camp differed from the share of references to research from home in year τ. Similarly, ι_τ measures how the share of references to research produced by foreign authors from inside the camp differed from the share of references from home. We plot the yearly coefficients in Figure IV. Even before WWI, papers contained fewer references to recent research from outside the camp, and even fewer references to foreign research from inside the camp, indicating a substantial home bias (Figure IV). After the onset of the war, relative citations to research from foreign authors declined sharply, particularly for citations to research from outside the camp. Relative citation shares to research from outside the camp declined from -0.35 before the war to about -0.71 at the end of the war and the early boycott, a decline of about 0.36. Relative citations shares to research from inside the camp declined from about -0.47 to -0.64, a decline of about 0.17. After 1919, citation shares began to recover but remained lower than in the pre-war period.

Citations to Frontier Research

In further results, we explore whether citations to frontier research were also affected. We define the frontier as research that ended up in the top percentiles (top 5%, top 3%, and top 1%) of the field-level citation distribution. We count the total number of citations of each piece of research until today, i.e. almost 100 years. This measure of the research frontier therefore captures the very long-run view of the quality of research and it is less likely to be affected by short-term scientific "fashions."[16]

[15] It is important to keep in mind that we analyze references produced in the preceding five years for these results. For a paper published in 1919, for example, we count references to research published between 1915 and 1919.

[16] Specifically, we divide the share of references to research from home into references that ended up in the top 5% of the distribution and references that ended up in the bottom 95%. Similarly, we divide the shares to research from inside

The share of references to top 5% research from outside the camp fell by 0.053, relative to references to top 5% research from home (Table V, column 1, significant at the 1 percent level), a reduction of 95 percent, relative to the pre-war share. By construction, the share of references that quote top 5% research is smaller than the share of references that quote research of any quality (see Table III), and hence, coefficients are likely to be smaller in absolute terms. However, in percentage terms the relative declines were similar. The point estimate becomes larger in absolute magnitude if we control for linear camp-specific trends (Table V, column 2).

The share of references to top 5% research from foreign authors inside the camp fell by 0.023 relative to top 5% research from home (Table V, columns 1 and 2), a reduction of 72 percent relative to the pre-war share. The relative decline in the share of references to top 5% research from outside the camp was significantly larger than the relative decline in the share of reference to top 5% research from inside the camp (p-value < 0.001). Yearly coefficients are reported in panel (a) of Figure V.

We also find that the share of references to top 3% or top 1% research from *outside* the camp fell significantly, with percentage declines of 95 and 131 percent respectively (Table V, columns 3-6, significant at 1 percent, also Figure V). The share of references to top 3% or top 1% research from foreign authors *inside* the camp also fell, but by less than the share of references to research from outside the camp (Table V, columns 3-6, significant at 1 percent, also Figure V). These results indicate that the war and the boycott not only affected citations to average research, but also had significant and large effects on citations to high-quality research.

Robustness

It is important to note that potential changes in relative quality of scientific output in the Allied or Central camp are unlikely to explain our findings, because such changes would have decreased the share of references to research from outside the camp for one of the camps, but would have increased the share for the other camp.

The results are robust to a number of alternative specifications: to restricting the sample of citing papers to papers by authors with a university position by 1914, to only measuring citations to research published by authors with a university position by 1914, and to normalizing citation shares by the total number of potentially citeable papers produced in each camp. We also show that results are somewhat stronger for Allied than for Central scientists (see appendix B.1 for details).

We also find that citation patterns in Neutral papers look quite different. Citations toward foreign research outside the Neutral camp do not decline during WWI or the boycott (see Appendix Figure A.10 and appendix B.3).

the camp and outside the camp. Hence, the data now contain six observations per paper. Citations to top research from home are the omitted category. The top 5% is measured at the subject level for all papers in the 160 journals in our data, independently of whether we can assign countries to authors and/or references. We construct analogous measures of citations to research that ended up in the top 3% or top 1% of the citation distribution.

3.2 Do Changes in Citations Reflect Changes in International Knowledge Flows?

The observed changes in citations could reflect of reduced international knowledge flows, i.e. scientists not being aware of foreign research. Alternatively, the changes in citations could be a result of political hostility, i.e. scientists knowing of foreign research but deliberately deciding not to cite it. If the effect were predominately driven by political hostility, presumably scientists also would have reduced citations to pre-war research. We investigate reductions in citations to pre-war research by investigating two cohorts of research (1903-1905 and 1911-1913).[17]

We find no evidence for a large dip in citations to pre-war research from foreign countries during WWI or the boycott (Figure VI). The share of references quoting pre-war research from foreign countries increased over time relative to the share of references quoting pre-war research from home (the excluded category), because even under normal conditions knowledge takes time to reach foreign countries. Over time, citations to less-relevant work from home fade, but good papers from all camps continue to receive citations. We also estimate the equivalent of equation (1) for all pre-war cohorts between 1903 and 1913. Citations to foreign research do not decline after 1914 for any of the nine pre-war cohorts (see Appendix Table A.9).

These auxiliary results suggest that the changes to citations of recent research (section 3.1) were predominately driven by scientists' lack of knowledge about recent foreign research, and not by political hostility. To further probe the effect of political hostility on citation shares, we also investigate citations to recent research for non-chemists. The involvement of prominent chemists in the development of chemical weapons led to particularly strong resentment of chemists in the opposing camp. If political resentment were the main driver of changes to citations to recent research, we would expect smaller changes to citations shares if we excluded chemists from the sample. However, the results do not change substantially if we omit chemists (see Appendix Figure A.7, panel b).

3.3 The Effect of WWI and the Boycott on the Similarity of Paper Titles

Using Latent Semantic Analysis to Measure the Similarity of Titles

To complement our citation analysis, we investigate how WWI and the boycott affected the similarity of papers produced in the different camps. We analyze the similarity of papers by applying Latent Semantic Analysis (LSA) (Deerwester et al., 1990; Landauer et al., 1998) to the titles of scientific papers. LSA is a machine-learning technique that retrieves semantic connections between words, so that even titles with completely different words can be classified as similar if the words are

[17] These results fix the cohort of research (either to 1903-1905 or to 1911-1913) and investigate how citation shares to those two cohorts changed over time. In contrast, the main citation results investigate citation shares to a moving window of references, i.e. references to research published between 1901 and 1905 for citing papers published in 1905, but to research published between 1902 and 1906 for citing papers published in 1906, and so on.

regularly used in similar contexts. For example, “n-dimensional,” “manifold,” and “topology” often appear together in paper titles. Therefore, LSA will classify a title that only contains “manifold” as similar to a title that only contains “topology.” Moreover, LSA recognizes when the same word is used in different contexts. Thus, LSA offers a significant improvement over measures of similarity based solely on word counts.[18]

Because ISI translated all titles into English, we do not have to consider differences in original publishing languages when applying LSA. We prepare the titles for LSA by removing stopwords and one-letter words. We then use a Snowball stemmer to reduce the words to their morphological roots, so called stems (Porter, 1980, 2001). Finally, we remove titles with fewer than five stems, because titles with very few stems may have artificially high similarity. This leaves us with 79,438 paper titles D and a vocabulary V of 35,119 unique word stems, i.e. terms, which we use to create a $D \times V$ document-term-matrix.[19] The individual word counts in the matrix are then reweighted by their term frequency-inverse document frequency. This re-weighting decreases the relative importance of words that carry little information but appear in many documents, e.g. “study.”

LSA uses Truncated Singular Value decomposition to reduce the dimensionality of the document-term-matrix from $D \times V$ to a user chosen number of components C (for a detailed explanation see Appendix C). The output of LSA is a $D \times C$ document-component matrix with rows δ_d of dimension $1 \times C$. The components capture the semantic relationships between the documents.

We then use the document-component matrix to measure the similarity of titles by calculating the cosine similarity, a standard similarity measure in machine-learning. The cosine similarity of document-pair i and j is defined as $\frac{\sum_{c=1}^{C} \delta_{i,c}\delta_{j,c}}{\sqrt{\sum_c \delta_{i,c}^2}\sqrt{\sum_c \delta_{j,c}^2}}$, where $\delta_{i,c}$ and $\delta_{j,c}$ are the elements inside the document-component matrix for documents i and j. The cosine similarity is 1 for titles that are identical and 0 for titles that are completely different. For each paper published in year t, we calculate the following three measures with respect to papers published between years $t-4$ and t:

1. the cosine similarity to the most similar paper at home (excluding papers by the same author),
2. the cosine similarity to the most similar paper by a foreign author inside its camp,
3. the cosine similarity to the most similar paper by a foreign author outside its camp.

We also calculate alternative similarity measures using the average cosine similarity for the five most similar papers from each camp. We standardize the similarity measures to have zero mean and unit variance (see Table III for average similarity to papers from each camp).

[18]LSA also outperforms other machine-learning techniques such as Latent Dirichlet Allocation (Blei et al., 2003) or Non-negative Matrix Factorization (Lee and Seung, 2001) in word-similarity tasks (Stevens et al., 2012).

[19]We apply LSA to all papers published between 1905 and 1930, independently of whether we know the country of authors and references, because a larger set of papers will improve the accuracy of LSA. When we estimate how title similarity changed during the war and the boycott we limit the sample to papers used in the analysis of citation shares.

The Effect of WWI and the Boycott on Title Similarity

For each paper, we create three observations with the title similarity to papers from each of the three camps (foreign outside the camp, foreign inside the camp, and home). We estimate equation (1) with LSA title similarity as the dependent variable. The parameters of interest are ω_2 and ι_2, which measure how the title-similarities changed after 1914, relative to the title similarity to papers produced at home.[20]

After 1914, the similarity to papers from outside the camp fell by 0.47 standard deviations (sd), compared to the similarity to papers from home (Table VI, column 1, significant at the 1 percent level). This result is robust to controlling for camp-specific linear time trends (column 2). The relative decline was 0.46 sd during WWI, 0.53 sd during the boycott, and 0.43 sd in the post-boycott years (column 3). The relative similarity to papers from inside the camp, however, did not change significantly after 1914 (Table VI, columns 1-3). The exception is a regression that controls for camp-specific linear time trends. According to this specification the similarity to papers from inside the camp fell by about 0.3 sd during the boycott and the post-boycott years (column 4).

The results are very similar when we measure title similarity to the five most similar titles from each camp (Table VI, columns 5-8). We also estimate yearly coefficients (Figure VII).[21] After the beginning of WWI, the similarity to papers from outside the camp fell sharply, relative to the similarity to papers from home, and started to recover in the 1920s but did not reach its pre-war levels until 1930. The relative similarity to papers from inside the camp also declined somewhat during the war, but less than the similarity to papers from outside the camp.[22] These results are robust to varying the number of components used to construct title similarity measures (Table A.11).

These findings corroborate the citation share results. It is important to note, that LSA title similarity is exclusively computed from the information in paper titles of citing papers. In contrast, citation shares are computed from information in the references and do not use information from the titles of citing papers. While these results indicate that the scientific communities in enemy camps diverged during this period, this does not mean that this divergence was necessarily neg-

[20]The number of observations is smaller than for the citation share regressions because we focus on papers with titles that have at least five words after stemming and removing stopwords. We also drop papers for which we cannot compute the similarity to the home camp because for small countries our data sometimes only contain one home paper published between year $t-4$ and t.

[21]In most years, the similarity to the most similar paper from foreign countries outside the camp is larger than the similarity to the most similar paper from foreign countries inside the camp, because the data contain more papers from the United States and Germany. The probability of finding a similar paper is higher if a camp produces more papers. For Germany, foreign countries inside the camp are small (e.g. Austria) and hence it is less likely that we find similar papers produced by foreign scientists inside the camp. In contrast, foreign countries outside the camp are large (e.g. the United States) and hence it is more likely that we find similar papers. A similar argument applies to U.S. papers.

[22]Because all titles are translated into English, the results are presumably not driven by diverging terminology in the two camps but rather by a divergence in the direction of research. As LSA recognizes semantic context, it would also classify titles as similar if scientists in opposing camps temporarily used different scientific terms but later converged to a common terminology.

ative for scientific progress. We therefore investigate effects on scientific productivity in the next section.

We also investigate changes in title similarity of Neutral papers. The results for Neutral papers look quite different. During the war and the boycott, the similarity to papers from both outside the Neutral camp and foreign countries inside the Neutral camp did not change, relative to the similarity to papers from home (Appendix Figure A.10).

The temporary divergence of title similarity could either be caused by reduced international knowledge flows or by a war-related divergence of research motivated by military needs. For example, chemists in the opposing camps may have developed weapons relying on different scientific foundations. Excluding chemistry papers from the similarity analysis hardly changes the results (see Appendix Figure A.9), even though scientists in other fields were less involved in the war effort. This suggests that the divergence of research was at least partly driven by reduced international knowledge flows.

4 Interruption of International Cooperation and Scientific Productivity

4.1 Publications in Top Scientific Journals

Next, we investigate whether the reduction of international scientific cooperation impacted scientific productivity. Because many scientists stress the importance of frontier knowledge, we compare productivity changes for scientists in fields that, in the pre-war period, relied on frontier knowledge from abroad to changes for scientists in fields that relied on frontier knowledge from home. The productivity of scientists who relied on frontier knowledge from abroad, particularly from outside the camp, should be disproportionately affected by the breakdown of international scientific cooperation.

We proxy reliance on frontier knowledge from the three camps (home, foreign countries inside the camp, and outside the camp) with pre-war citation shares, measured at the field-country level. Specifically, we compute citation shares in papers published by scientists in each field-country pair between 1905 and 1913. We also compute citation shares to non-frontier research from the three camps. In Figure VIII, panel (a), we show how certain field-country pairs (e.g. chemistry in the United States), in the pre-war period, depended on research from home, foreign countries inside the camp and outside camp. In panel (b) we show pre-war dependence on frontier research.

A useful example of the identifying variation is the dependence on frontier research of biochemistry and biology in the United States. For U.S. scientists, knowledge from outside the camp came predominantly from Germany, while knowledge from foreign countries inside the camp came mainly from Britain. In biochemistry, Germany led the world in the early 20th century, e.g. the term "biochemistry" was coined by Carl Neuberg in 1903. Biochemistry in Britain and the United States, however, had yet to take off. This was reflected in the pre-war citation shares to frontier research of U.S. biochemists: 32 percent cited research from *outside the camp*, 12 percent from *inside the camp*, and 56 percent from *home*.[23] In biology, however, Germany's influence was less pronounced, while Britain, and in particular the United States, contributed many important discoveries. This was reflected in pre-war citation shares to frontier research of U.S. biologists: 6 percent cited research from *outside the camp*, 27 percent from *inside the camp*, and 67 percent from *home*.[24]

Average productivity of scientists in our sample declined during WWI and the boycott (see Appendix Figure A.11). We estimate the *differential* effect of the reduction in international scientific cooperation on productivity in a generalized differences-in-differences framework. We compare productivity changes of Allied and Central scientists in country-field pairs that relied on frontier research from foreign countries outside the camp and inside the camp, to productivity changes of scientists who relied on frontier research from home.[25]

$$\begin{aligned} Outcome_{ift} &= \beta_1 \cdot (\text{Pre-War Reliance on Frontier OUT})_{if} \times 1\,[t = \text{Post 1914}] \\ &+ \beta_2 \cdot (\text{Pre-War Reliance on Frontier IN})_{if} \times 1\,[t = \text{Post 1914}] \qquad (3) \\ &+ \text{Scientist}FE_{if} + \text{Year}FE_t + X_{ift}\theta + \epsilon_{ift}. \end{aligned}$$

For the first set of results, the dependent variable measures the number of publications per year for each scientist. The coefficients β_1 and β_2 measure productivity changes relative to scientists in field-country pairs that relied on frontier research from home (the excluded category). The regression includes a full set of scientist fixed effects that control for permanent differences in quality across scientists. The regression also includes a full set of year fixed effects that control for yearly changes in productivity that affected all scientists in the same way, such as a reduction in productivity during the war years. We also control for the reliance on non-frontier research from home, foreign countries inside the camp, and outside the camp, all interacted with post-1914 indicators. Furthermore, we control for five-year career-age indicators interacted with the main field of each scientist, i.e. we

[23]Note that scientists in large countries across all fields disproportionately cited research from home. Our identifying variation relies on field-country level differences in citations to research from home, foreign countries inside the camp, and outside the camp. Differences in the pre-war reliance on foreign research between field-country pairs occur because field-country pairs produced different amounts of frontier research before the war (see Appendix D for a stylized example of the identifying variation).

[24]To simplify the exposition, our example and panel (b) in Figure VIII focus on frontier research. However, in all regressions we use the pre-war share of references quoting frontier research from home, non-frontier research from home, frontier research from foreign authors inside the camp, non-frontier research from inside the camp, frontier research from outside the camp, and non-frontier research from outside the camp. For the main results presented in the paper we require that scientists in a certain field-country pair published at least five papers before 1914 to construct the pre-war dependence on research from home, foreign countries inside the camp, and foreign countries outside the camp. Choosing a higher threshold of pre-war papers, e.g. at least 10 papers, leads to very similar results (see Appendix Table A.13)

[25]For scientists who worked in multiple fields, e.g. physical chemistry and chemistry, we assign the reliance on frontier and non-frontier research from the different camps according to the share of their publications in each field.

control for different career-age productivity profiles for physicists, chemists, and so on. We estimate regression (3) for scientists who had a university position by 1914. This prevents potential selection bias caused by scientists of different quality entering or exiting the sample. The data contain 8,734 scientists with yearly productivity information for the years 1905 to 1930, which results in 227,084 person-year observations (Table VII). Standard errors are clustered at the country-times-field level.[26]

We estimate this regression for different definitions of the research frontier (top 1%, top 3%, or top 5%). Scientists in field-country pairs that relied on top 1% research from outside the camp published significantly less after 1914, compared to scientists who relied on top 1% research from home (Table VIII, column 1, significant at the 1 percent level). The estimated effect implies that scientists in a field-country pair that, in the pre-war period, cited a lot of frontier research from outside the camp, such as biochemistry in the United States, published 0.1 of a standard deviation fewer papers per year after 1914 (i.e. 0.15 fewer biochemistry papers per year, a reduction of 33 percent), compared to scientists in field-country pairs that cited a lot of frontier research from home, such as U.S. biology. A field-country pair with one of the highest pre-war reliance on frontier research from outside the camp was physics in Italy. Compared to a field-country pair that cited only frontier research from home, the estimated coefficient implies that Italian physicists published 0.27 standard deviations fewer papers per year after 1914 (i.e. 0.28 fewer physics papers per year, a reduction of 55 percent).

The productivity of scientists in field-country pairs that, in pre-war period, cited a lot of top 1% research from inside the camp also published less after 1914, but not significantly so (Table VIII, column 1). The point estimate suggests that the relative productivity decline for scientists reliant on frontier research from inside the camp was about half as large as the productivity decline for scientists reliant on frontier research from outside the camp. This lines up well with the impact of WWI and the boycott on citation shares to frontier research from inside and outside the camp that we have shown in the first part of the paper (e.g. Table V, columns 1, 3, and 5).

To understand the timing of these effects, we estimate yearly coefficients:

$$\begin{aligned} Outcome_{ift} &= \sum_{\tau=1905(\tau\neq1913)}^{1930} \beta_{1\tau} \cdot (\text{Pre-War Reliance on Frontier OUT})_{if} \times 1\left[t=\tau\right] \\ &+ \sum_{\tau=1905(\tau\neq1913)}^{1930} \beta_{2\tau} \cdot (\text{Pre-War Reliance on Frontier IN})_{if} \times 1\left[t=\tau\right] \\ &+ \text{Scientist}FE_{if} + \text{Year}FE_t + X_{ift}\theta + \epsilon_{ift}. \end{aligned} \tag{4}$$

Scientists in field-country pairs that relied on frontier research (as measured by the top 1%) from outside the camp suffered a sharp decline in productivity after 1914, compared to scientists who relied on frontier research from home (Figure IX). For these scientists, relative productivity did not recover. Scientists in field-country pairs that relied on frontier research from inside the camp suffered

[26]We assign each scientist to his main research field according to his publications in each field.

a smaller decline in productivity after 1914, which was not persistent. The figure also indicates that pre-trends cannot explain the results. Scientists in field-country pairs that relied on frontier research from outside the camp, relative to frontier research from home, improved in the years until 1913, suggesting that, if anything, we underestimate the effect of the war and the boycott.[27] After 1913, however, the productivity of scientists in field-country pairs that relied on frontier knowledge from outside the camp declined sharply. Similarly, the figure indicates that pre-trends cannot explain the productivity decline of scientists in field-country pairs that relied on frontier research from inside the camp, relative to scientists in field-country pairs that relied on frontier research from home.

If we alternatively measure the research frontier with top 3% research, we estimate a smaller, but still highly significant, productivity decline for scientists who relied on frontier research from outside the camp, compared to scientists who relied on frontier research from home. If we measure the frontier with top 5% research, we estimate an even smaller, but still significant, decline in productivity (Table VIII, columns 2 and 3, significant at the 1 percent and 10 percent level, respectively). Scientists who relied on frontier research from foreign countries inside the camp suffered smaller and insignificant productivity declines. We test whether the productivity decline after 1914 was significantly larger for scientists reliant on frontier research from outside the camp than for scientists reliant on frontier research from inside the camp. For the different definitions of the knowledge frontier we get the following p-values: 0.136 (1% frontier), 0.055 (3% frontier), and 0.124 (5% frontier). For the most stringent specification with camp-times-field-times year fixed effects (see Table IX below) the p-values are: 0.147 (1% frontier), 0.007 (3% frontier), and 0.012 (5% frontier).

The alternative measures of frontier research suggest that the knowledge frontier is narrow-edged. Scientists who lost access to top 1% research experienced productivity declines that were about twice as large as the productivity declines of scientists who lost access to top 3% or top 5% research.[28]

Including Additional Fixed Effects

For the previous results, we normalize the dependent variable by the number of authors per paper. Without this normalization, the results remain very similar (Table IX, column 2). Furthermore, the results are qualitatively unchanged if we include additional fixed effects (Table IX, columns 3-5). These fixed effects control for various potential confounders that may be correlated with the propensity of citing frontier research from outside the camp, inside the camp, or home in the pre-war period. In particular, we control for camp-times-year fixed effects to allow for cross-camp differences in productivity in each year (column 3). We also control for field-times-year fixed effects which allow for cross-field (e.g. chemistry in 1915) differences in productivity in each year. Finally, we control

[27] We report yearly coefficients and standard errors in Appendix Table A.12.

[28] We measure top 1%, top 3%, and top 5% percent as the field-level percentiles within the 160 top scientific journals in our data. As these journals are the highest-cited journals of the time, the top 1% corresponds to an even more selected part of the overall citation distribution.

for camp-times-field-times-year fixed effects which allow for cross-camp-and-field differences (e.g. chemistry in Allied countries in 1915) in productivity in each year. In the latter specification, the effect is identified from variation in the pre-war reliance on foreign research between fields within the same camp, e.g. biology in the United States, the United Kingdom, and other Allied countries.[29] These fixed effects control for a differential impact of any shock that has the same effect on scientists' productivity in the a certain field, camp, and year. For example, Allied chemists may have published less in 1919 because of their involvement in the organization of the boycott against Central scientists. Similarly, these fixed effects control for scientific breakthroughs that made scientists in a field and camp more productive in a certain year, e.g. Central physicists (among them Werner Heisenberg from Germany and Erwin Schrödinger from Austria) at the height of the quantum revolution.

Potential Confounding Effects of WWI on Scientific Productivity

In additional specifications, we show that the results are presumably driven by a reduction in international knowledge flows, and not by more general disruption caused by WWI. While camp-times-field-times-year fixed effects control for yearly productivity shocks that affect all scientists in a certain camp and field, some war-related confounders may potentially be correlated with the dependence on frontier research from abroad.

While the war was not fought on the territories of the most important scientific powers (the United States, the United Kingdom, and Germany), it may nevertheless have disrupted scientific research in some field-country pairs because of other issues. For example, professors may have had fewer graduate students for joint projects because potential students were drafted, or professors may have been distracted by political engagement or by worries about the safety of their families and friends. While we do not have direct measures for these confounders, we proxy for them with different country-level measures of war intensity that we interact with year fixed effects. The results are robust to controlling for an indicator of combat on the territory of the country, the total number of deaths per capita, the total number of civilian deaths per capita, and all three war-intensity measures at the same time (Table X, columns 1-4).[30]

To investigate whether the war had a more direct effect on the mortality of scientists in our sample, we collect data on more than 6,500 obituaries from *Science*, *Nature*, *Physikalische Zeitschrift*, *Sitzungsberichte der Preussischen Akademie der Wissenschaften*, and *Kürschners Deutscher Gelehrtenkalender* and match them to the sample of scientists with a university position by 1914 (see Appendix E.6 for details). In general, scientists in our sample did not die disproportionately during WWI (Appendix Figure A.12). Moreover, we also show that scientists reliant on frontier research from abroad did not die disproportionately during this period (Appendix Table A.14).

[29] Differences in the pre-war reliance on foreign research between fields within the same camp occur because field-country pairs produced different amounts of frontier research and because, even in normal times, frictions reduce knowledge flows across countries (see Appendix D for a stylized example of the identifying variation).

[30] See Appendix E.5 for data sources on war-intensity measures.

The results are also robust to excluding chemists, whose scientific productivity may have been differentially affected by research on chemical weapons during the war (Table X, column 5). While camp-times-field-times-year fixed effects control for most of these changes, the propensity to engage in war-related research among chemists may have been correlated with the pre-war reliance on frontier research from abroad. For example, U.K. chemists, who were more reliant on research from abroad, may have been more distracted by research on chemical weapons than U.S. chemists, who were less reliant on research from abroad.

Finally, scientists in field-country pairs that, in the pre-war period, were heavily reliant on frontier research from outside the camp may have published more papers in journals from the other camp during normal times. Thus, in addition to contending with reduced international knowledge flows, these scientists may have faced greater difficulty in publishing their papers during a time of political hostility. We explore this possibility by focusing on publications in own-camp journals. The results remain unchanged (Table X, column 6), presumably because the majority of scientists published in journals edited in their own camp (see Appendix Table A.4).

Field-level Variation Within the United States

We also explore effects on productivity using variation across fields in the United States only. Some U.S. fields, such as biochemistry, relied on frontier research from outside the camp, while others, such as biology, relied mostly on frontier research from home. While the United States participated in WWI, no battles were fought on U.S. territory, and hence, war-related disruption may have impacted U.S. scientists to a lesser extent. Furthermore, this analysis allows us to rule out that the results are driven by a general rise of U.S. science that may have been correlated with the pre-war dependence on foreign research.

In the pre-war period, the productivity of U.S. scientists in fields that relied on frontier research from outside the camp improved, relative to the productivity of scientists in fields that relied on frontier research from home (Figure X). After 1914, the productivity of scientists in fields that relied on frontier research from outside the camp declined sharply and did not recover until 1930. We test whether the trend-break in 1914 is statistically significant with a regression that includes linear trends and the interaction of each linear trend with a post-1914 indicator.[31] The estimated trend-break in 1914 for the "Pre-War Reliance on Frontier *OUT*" has a p-value of 0.055. The productivity of U.S. scientists in fields that relied on frontier research from foreign countries inside the camp also improved in the pre-war period. While the productivity of scientists in these fields continued

[31] More specifically, we estimate regression (3) including linear trends for "Pre-War Reliance on Frontier *OUT*," "Pre-War Reliance on Frontier *IN*," and "Pre-War Reliance on Frontier Home," plus non-frontier trends and the interaction of each of these trends with a post-1914 indicator. We then test whether "Pre-War Reliance on Frontier *OUT*" interacted with "post-1914" is significantly different from 0. The U.S. sample includes 11 fields and we cluster standard errors at the field level. To avoid a downward bias in estimated standard errors due to the small number of clusters (Cameron et al., 2008), we implement a cluster-bootstrap with asymptotic refinement as suggested by Cameron and Miller (2015).

to improve after 1914, it improved at a somewhat lower pace. The trend-break in 1914 for the "Pre-War Reliance on Frontier *IN*" was smaller than for scientists in fields that relied on frontier research from outside the camp (p-value of 0.099).

4.2 Alternative Outcomes

The previous results indicate that scientists in field-country pairs that, in the pre-war period, relied on frontier research from abroad, published significantly fewer papers in top journals after 1914. In the following section, we explore whether this decline in the quantity of research (published in top science journals) was associated with a decline in the impact of that research on basic science and technology. In this context, paper citations as a measure of impact are problematic because citations were heavily distorted during the war and the boycott, as highlighted in the first part of the paper. We therefore investigate effects on three new measures of research impact: Nobel-nominated research, scientific research that introduced novel words, and a measure of how often these words were applied in U.S. patents.

4.2.1 Nobel-Nominated Research

To investigate effects on path-breaking research, we analyze changes in the probability of producing research that led to a Nobel Prize nomination. The Nobel Prize has been awarded by the Academy of Sciences and the Karolinska Institutet in Sweden, a *Neutral* country.

We collect data on all nominations for the physics, chemistry, and physiology/medicine prizes from the Nobel Nomination Archive (see Nobelprize.org, 2014). Between 1905 and 1945, 993 individuals were nominated for a Nobel Prize at least once, and 131 of them eventually won it. The database does not list the exact research that led to a nomination. We identify that research by searching our publication data for the highest-cited paper (counting citations until today) that a nominee published before his last nomination (see Appendix E.4.5 for details).[32] We then generate an indicator, "Nobel-nominated paper" that equals one if a scientist published his "Nobel-nominated paper" in a certain year, and zero for all other years.

For example, Arthur Compton received the 1927 Nobel Prize in physics "for the discovery of the effect named after him." He was last nominated for the prize in 1927, and we therefore search for the highest-cited paper that he published before 1927. His article, "A quantum theory of the scattering of x-rays by light elements," was published in the *Physical Review* in 1923, and received

[32] Ideally, we would not rely on citations to identify the year of Nobel-nominated research. However, this year cannot be systematically identified from the data posted by the Nobel archives. Jones and Weinberg (2011) collect biographical data to identify the period of key research for Nobel Prize winners. Our measure of Nobel-nominated research identifies a single year. For Nobel Prize winners, our measure has a correlation of 0.69 with the middle year of the period of key research reported by Jones and Weinberg. The detailed information that Jones and Weinberg use to construct their measure is not available for scientists who were nominated but did not win.

(until today) 355 citations, more than any other of his pre-1927 papers. For Arthur Compton the "Nobel-nominated paper" indicator therefore equals one in 1923, and zero in all other years.

While some candidates "only" received one nomination for the Nobel Prize, others received many more. To distinguish papers at the very highest level of the quality spectrum, we construct a second measure that weighs the Nobel-nominated papers by the number of nominations. Because scientists who eventually won the prize experienced a hike in nominations in the last two years before winning (Appendix Figure A.14), we focus on the number of nominations during the last two years before a candidate's last nomination. The physicists with the highest number of nominations in the last two years were Albert Einstein (31 nominations), Jean Perrin (18), Werner Heisenberg (17), and Erwin Schrödinger (17); they all eventually won the Nobel Prize, and they are considered to have made some of the most outstanding contributions to physics in this period. The measure is highly predictive of winning the Nobel Prize.[33] Candidates with one nomination only had a 4 percent chance of winning. Candidates with two nominations had a 13 percent chance, candidates with three nominations had a 16 percent chance, candidates with four nominations had a 19 percent chance, candidates with five to nine nominations had a 40 percent chance, and candidates with more than nine nominations had a 61 percent chance of winning (Appendix Figure A.13).

Using the "Nobel-nominated paper" variable as the dependent variable, we estimate regression (3) for our sample of university scientists.[34] After 1914, the probability of publishing a Nobel-nominated paper declined significantly for scientists in field-country pairs that relied on frontier research (measured by the top 1%) from outside the camp (Table XI, panel A, column 1, significant at the 5 percent level). The estimated effect indicates that the probability of publishing a Nobel-nominated paper declined by 0.001 for scientists in a field such as U.S. biochemistry that relied heavily on frontier research from outside the camp, compared to scientists in a field such as U.S. biology that relied mostly on frontier research from home. The pre-war period probability of writing a Nobel-nominated paper in fields that relied on frontier research from abroad is also 0.001. Thus, the results indicate that the decline in international scientific cooperation effectively wiped out the chance of writing a paper worthy of a Nobel Prize nomination for scientists in field-country pairs reliant on frontier research from outside the camp. The results are robust to using different definitions of frontier research (panels A to C) and to adding camp-times-field-times-year fixed effects (column 2). We obtain similar results if we weigh the Nobel nominated indicator by the number of nominations (Table XI, columns 3 and 4).

These results suggest that access to the very best research, especially the top 1%, is key for the production path-breaking ideas.

[33] The number of nominations in the last two years before the last nomination is a better predictor of winning than the total number of nominations, because the total number of nominations is censored for winners (i.e. most of them were no longer nominated after winning).

[34] The estimation includes 234 nominees, among them 42 winners. Of the 993 potential nominees, 474 published their Nobel-nominated paper between 1905 and 1930, and 234 of them had a university position by 1914.

4.2.2 Novel Scientific Words

As an alternative outcome, we count the number of novel words that a scientist introduced to the scientific community in each year. The measure proxies for the introduction of new scientific concepts that required new scientific terms. We define novel words as words that the scientist first used in a title of a paper published between 1905 and 1930, and that had not been used in any prior paper title. To check whether a word had been used before, we not only consider the papers published by the scientists in our estimation sample, but all papers that were published in any of the 160 journals in the Web of Science between 1900 and 1930. To assure that we do not consider words that were already commonly used in other domains, we exclude frequently used words, as well as all numbers, from the data.[35] As above, we standardize the outcome variable to have mean zero and unit variance within fields.

One example of a novel word is "magnetron," which was introduced by U.S. physicist Albert W. Hull in the paper "The measurement of magnetic fields of medium strength by means of a magnetron," published in the *Physical Review* in 1923. Another example is "electroencephalogram," which was introduced by German psychiatrist Hans Berger in the paper "Electroencephalogram of humans," published in the *Journal für Psychologie und Neurologie* in 1930.[36] Other examples of novel words that were introduced in this period are hormone, isotope, superconductor, and chemical substances such as 5-trinitro-4-acetylaminophenol. Introducing novel words is rare; the average scientist introduced 0.042 novel words per year (Table VII).[37]

Using the number of novel words as the dependent variable, we estimate regression (3). After 1914, scientists in field-country pairs that relied on frontier research (measured by the top 1%) from outside the camp published fewer papers that introduced novel words (Table XII, panel A, column 1, significant at the 1 percent level).[38] The estimated effect indicates that scientists in a field such

[35]We exclude the 10,000 most frequently used words in English-language books contained in the Project Gutenberg database as of April, 16, 2006 (available at https://en.wiktionary.org/wiki/Wiktionary:Frequency_lists#English). Project Gutenberg currently contains the full text of over 53,000 books. Because the database contains books whose copyright have expired, the typical book in the database was published before 1923. The most frequently used words therefore reflect historical language use that is more relevant for the period of our analysis. The results are robust to excluding only 5,000 or all 36,662 frequently used words (see Appendix Table A.15). For the main results, we do not remove all frequently used words because words such as quantum (on position 17,132) may have existed before but may have taken on a new meaning with the publication of a scientific paper. For more detail on the novel scientific words measure see Appendix (E.4.6).

[36]Scientists typically publish a number of papers summarizing an important discovery. We count the first appearance of a novel word in the 160 journals in our data, which may not necessarily be the very first time the word appeared in any scientific publication. Albert Hull, for example, published a paper "The magnetron" in the *Journal of the American Institute of Electrical Engineers* in September 1921. This journal is not in our data because it was not a core journal for scientists in the mathematics, physics, chemistry, biology, or medicine.

[37]The total number of novel scientific words that a scientist introduced in papers published between 1905 and 1913 has a correlation of 0.51 with the total number of citations that these papers have received until today.

[38]The number of novel words would increase artificially if scientists in opposing camps started to use different terms for the same scientific concept after 1914. Our measure of novel words is less susceptible to this concern because ISI translated all paper titles into English in 2004. Furthermore, more international field-country pairs should be more exposed to such an artificial increase in the number of words. This would bias our estimates towards zero.

as U.S. biochemistry, that relied heavily on frontier research from outside the camp, introduced 0.07 standard deviations fewer words than scientists in a field such as U.S. biology that relied mostly on frontier research from home. Scientists who relied on frontier research from inside the camp also published fewer papers that introduced novel words (Table XII, panel A, column 1, significant at the 10 percent level). When we measure the frontier with the top 3% or top 5% of research, we only find significant effects in specifications that add camp-times-field-times-year fixed effects (Table XII, panels B and C, columns 1 and 2). As before, the results are strongest if we measure the frontier with the top 1% of research, suggesting that access to the top 1% is particularly important to produce papers that introduce new scientific concepts.

4.2.3 Novel Scientific Words that Are Applied in Technology

We also investigate an outcome that measures how basic science was applied in the development of new technologies. Specifically, we measure how often subsequent patents used the novel words that were introduced to the scientific community (as described in the previous section). We obtain the full text of 2.5 million patents that were granted between 1920 and 1979 from the U.S. Patent Office web page.[39] We then search the 7.5 billion words in these patents for the novel words that scientists in our sample introduced to the scientific community. For a paper published in year t, the measure counts the number of times a novel scientific word appears in subsequent patents that were granted between year $t + 15$ and $t + 30$. As an example, for a paper published in year $t = 1905$ which introduced a novel word, we search patents granted between 1920 and 1935.[40]This measure of patent-relevant words weighs the novel scientific words introduced by each scientist in a certain year with the number of times these words appear in subsequent patent grants.[41]

For example, the novel scientific word "magnetron," which was introduced in 1923, appeared 9,538 times in 997 patents after 1923. The magnetron was later used to dramatically improve radar technology. It serves at the heart of the microwave ovens, and provides the key underlying technology for sulfur lamps. Examples of patents that use the word "magnetron" are U.S. patent number

[39]Ideally, we would search patents that were granted from 1905 onward, but unfortunately the full text of 1905 to 1920 patents is neither available from the U.S. Patent Office web page nor from other sources.

[40]The time window ensures that we measure the link between basic science and technology with a consistent time delay. This accounts for the fact that patent data are only available from 1920 inwards. As a result of this data limitation, novel words that were introduced in scientific papers published in 1905 can only be observed in patents after 15 years. While the data structure leads us to measure effects of basic science on patenting with a 15-year delay, earlier research shows that basic pharmaceutical research is associated with U.S. Federal Drug Administration approval of new molecular entities with a delay of 17 to 24 years (Toole, 2012), and that the stock of basic science affects total factor productivity growth with a delay of about 20 years (Adams, 1990). The results are robust to considering all patents granted between 1920 (or the publication year of the relevant paper if it was published after 1920) and 1979 (see Appendix Table A.16, columns 11-12).

[41]This measure may overstate the effect of basic science on the development of new technology if certain novel words appeared independently of each other in papers and patents. As long as independent discoveries did not change differentially across field-country pairs over time, the estimates of the effect of reduced international cooperation would remain unbiased.

2,115,521 “Magnetron Oscillator and Detector” granted in 1939, and U.S. patent number 2,605,383 “Means of treating foodstuffs,” one of the first microwave patents granted in 1952. The novel word “electroencephalogram,” which was introduced in 1930, appeared seven times in three patents after 1930. The electroencephalogram allows monitoring of electrical activity in the brain, and it is used to diagnose epilepsy, coma, and brain death. In the past, it was used to diagnose tumors and stroke, but this use declined with the invention of CT and MRI scans. An example of a patent that uses the word “electroencephalogram” is U.S. patent number 2,409,033 “Electroencephalograph device” granted in 1946.

Per year, the average scientist introduced novel words that appeared 0.43 times in subsequent patents. The number of novel scientific words that are applied in new technology is highly skewed because most scientists never introduced a novel scientific word, but a few scientists introduced words that were frequently applied in patents, for example “magnetron” appeared 9,538 times. To avoid that a few outliers drive the results, we winsorize the outcome variable at the 99th percentile.[42] We also standardize the outcome variable to have mean zero and unit variance within fields.

Using patent-relevant words as the dependent variable, we estimate regression (3). After 1914, scientists in field-country pairs that relied on frontier (measured by the top 1%) research from outside the camp published less scientific research that introduced novel words relevant for patenting (Table XII, panel A, column 3, significant at the 1 percent level). The estimated effect indicates that scientists in a field such as U.S. biochemistry, that relied heavily on frontier research from outside the camp, reduced patent-relevant words by 0.05 standard deviations compared to scientists in a field such as U.S. biology that relied mostly on frontier research from home. Scientists reliant on frontier research from inside the camp also reduced patent-relevant words, although this result is only significant if we control for camp-times-field-times-year fixed effects (Table XII, panel A, columns 3 and 4). When we measure the frontier with the top 3% or top 5% of research, we only find significant reductions in patent-relevant words for scientists in fields that predominantly relied on frontier research from outside the camp (Table XII, panels B and C, columns 3 and 4).

There are two main reasons why the patent-relevant word measure changed after 1914 in field-country pairs reliant on frontier research from abroad, relative to field-country pairs reliant on frontier research from home. First, because scientists in field-country pairs reliant on frontier research from abroad introduced fewer novel scientific words. Hence, the papers of these scientists would have been less useful for inventors. As a result, the scientists’ patent-relevant word measure would have decreased. Second, inventors themselves may have lost access to basic science from abroad. If inventors had sourced basic science research similarly to scientists, the patent-relevant word measure would have increased for scientists in field-country pairs reliant on frontier research from abroad.[43] As we find a relative decline in patent-relevant words for scientists in field-country

[42] The results are similar if we do not winsorize the data (see Appendix Table A.16).

[43] The following example illustrates the second channel: consider U.S. inventors who lost access to basic science from Germany. If U.S. biochemistry inventors had relied on basic science from Germany and U.S. biology inventors had relied

pairs reliant on frontier research from abroad, the results indicate that these scientists introduced fewer novel words that were useful for inventors. This suggests that the decline in international scientific cooperation not only affected the production of basic science but also impeded the application of basic science in the development of new technologies.

4.3 Who Benefits from Access to Frontier Research

Finally, we investigate whether high or low quality scientists are differentially affected by the reduction in international scientific cooperation. We split the sample into high and low quality scientists according to the field-level median productivity in the pre-war period, as measured by publications in the 160 top journals in our data. We then separately estimate regression (3) for high and low quality scientists.

Output of above median productivity scientists decreased five to 15 times more, in absolute terms, than output of below median scientists (Table XIII). These findings are consistent across all outcomes (columns 1 to 10) and the different definitions of frontier research (panels A to C). We measure output in absolute terms in order to capture overall scientific progress. However, relative to pre-war means, output declined relatively more for below median scientists.[44]

These results suggest a complementarity between access to frontier research and the underlying quality of scientists.

5 Conclusion

The dramatic decline in international scientific cooperation around WWI enables us to study how frontier research affects scientific productivity. This period sheds light on the importance of path-breaking research circulating among the most fertile minds in academic communities worldwide. Because our results suggest that access to frontier research is key for the production of ideas, including path-breaking ones, one can conclude that facilitating access to frontier research can substantially increase the production of basic science. Access needs to be interpreted in a broad sense: not only physical access to journal articles, conferences, and research seminars but also discerning the thin, ever-advancing, and truly path-breaking edge of the frontier from the millions of scientific papers published every year.

Our results suggest, that science policy should therefore be geared towards facilitating access to and capitalizing on the potential catalytic effects of frontier research in enhancing scientific progress.

on basic science from home, U.S. biochemistry inventors would have disproportionately reduced the application of basic science from Germany. As a result, the patent-relevant word measure of *German* scientists would have been affected: German biologists (reliant on frontier research from abroad) would have experienced an increase in the patent-relevant word measure, relative to German biochemists (reliant on frontier research from home).

[44]Due to the very low pre-war means of below median scientists, we find larger relative changes for these scientists. If, alternatively, we measure changes relative to 1905-1930 means, relative changes are larger for above median scientists.

Providing open access to journals may partly achieve this goal. However, discerning what constitutes frontier research requires skills that are hard to develop without guidance from leading scientists working at the forefront of scientific endeavor. Personal contacts are particularly useful because face-to-face interactions are a superior way of transmitting ideas (e.g. Glaeser, 2011, Head et al., 2015). High-quality PhD programs at universities where frontier research proliferates can therefore help to put young scientists on the most-promising career paths (Waldinger, 2010). Even more established scientists can profit from long-term and short-term visits at the centers of science (Catalini et al., 2016) and from attending high-quality conferences (de Leon and McQuillin, 2015) and research seminars. A famous example of a fruitful interaction between researchers is the series of lectures that Danish physicist and Nobel Laureate Niels Bohr held at Göttingen in 1922, sometimes dubbed the 'Bohr Festival.' At this event, Bohr presented his latest theories of atomic structure, and exchanged ideas with his peers, including (future) Nobel Laureates James Franck, Max Born, Wolfgang Pauli, and the young physics prodigy Werner Heisenberg (e.g. Mehra and Rechenberg, 1982, pp. 345). In fact, Bohr underscored that being from a small country made it even more important to interact with international scientists producing frontier research (Bohr, 2007, p. 172).

Our results also suggest access to frontier research not only affects the production of basic science but also increases the application of science in the development of new technology. Hence, policies that widen access to frontier research could benefit society beyond the confines of science itself.

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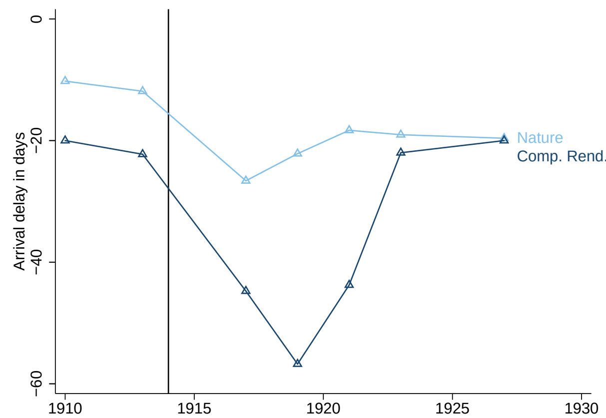
Figures

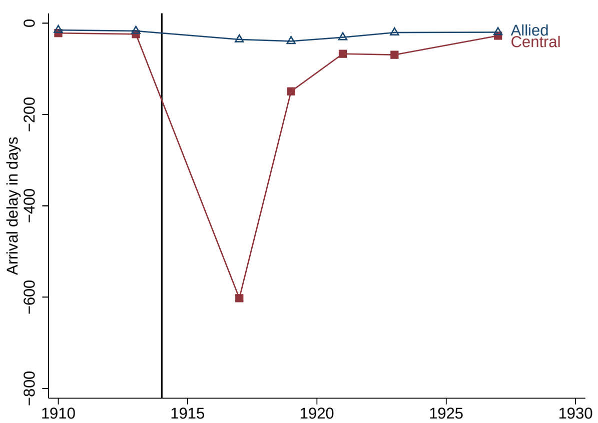
Figure I:
Arrival Delay of International Journals

(a) Central Journals at Harvard

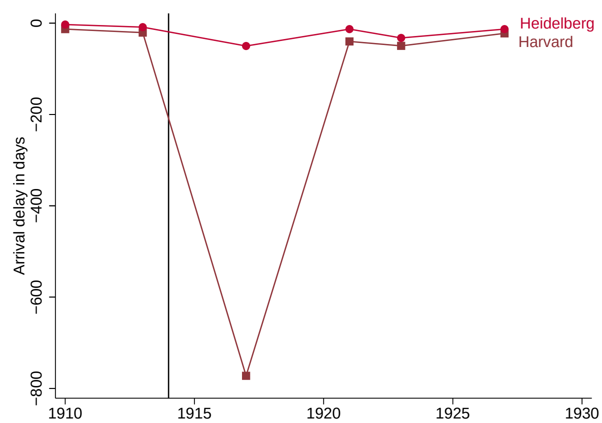
(b) Foreign Allied Journals at Harvard



(c) Central and Foreign Allied Journals at Harvard



(d) Annalen der Physik at Harvard and Heidelberg



Notes: Panel (a) plots the average delay between publication and arrival date at the Harvard library for the German journals *Zeitschrift für analytische Chemie* and *Annalen der Physik*. Arrival dates are based on library entry stamps (see Appendix Figure A.1 for an example). Delays are calculated as yearly averages for 1910, 1913, 1917, 1919, 1921, 1923, and 1927. Panel (b) plots the delay for two Allied journals, the British journal *Nature* and the French journal *Comptes Rendus*. Panel (c) compares average delays for German journals and Allied journals. Panel (d) compares delays for the *Annalen der Physik* at Harvard and at the University of Heidelberg in Germany. In Panel (d), the delay at Harvard differs slightly from the delay reported in panel (a) because we focus on journal issues that were available both at Harvard and at Heidelberg. Data on entry stamps were collected by the authors at Harvard and at the University of Heidelberg (see Appendix E.1 for details).

Figure II:
CENTRAL ATTENDANCE AT SOLVAY CONFERENCE

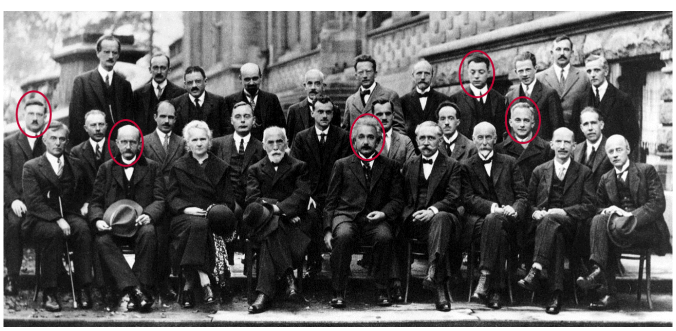
(a) 1911

(b) 1913

(c) 1921

(d) 1924

(e) 1927



(f) 1930

Notes: The Figure shows delegates at the *Solvay Conferences* in physics. Circles indicate delegates from Central countries. See Appendix Table A.2 for delegate names. Data were collected by the authors from Mehra (1975) (see Appendix E.3 for details).

Figure III:
Example citing paper and references

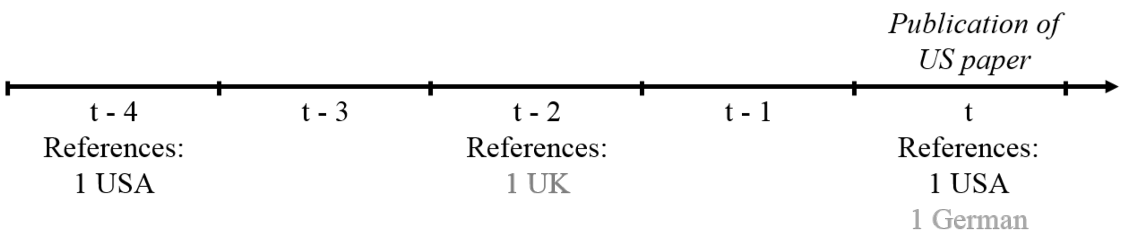
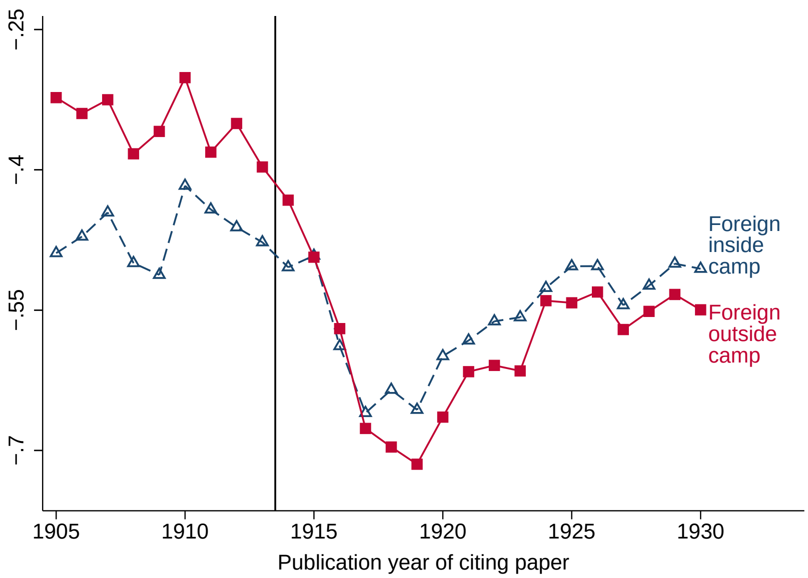


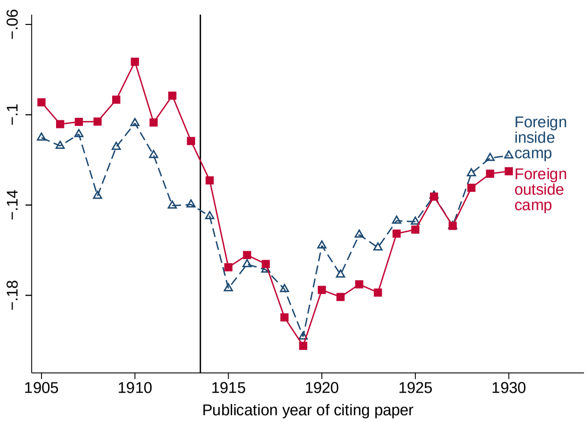
Figure IV:
International Citation Shares Relative to Home



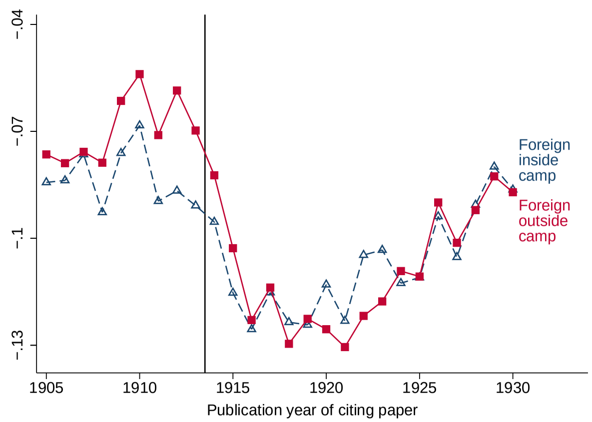
Notes: The Figure plots parameter estimates of regression (2). The "Foreign outside camp" line reports point estimates (ω_τ) that measure citation shares to research from outside the camp, relative to research from home. The "Foreign inside camp" line reports point estimates (ι_τ) that measure citation shares to research from foreign scientists inside the camp, relative to research from home. We count citations to recent research, i.e. research published in the preceding five years. For example, the first dot (1905) measures relative citation shares to research published between 1901 and 1905. The second dot (1906) measures relative citation shares to research published between 1902 and 1906, and so on. Point estimates and corresponding standard errors are reported in Appendix Table A.5. All point estimates are significantly different from 0 at the 1 percent level. The data were collected by the authors and combine scientist census data from *Minerva - Handbuch der Gelehrten Welt* and publication and citation data from *ISI - Web of Science* (see section 2 for details).

Figure V:
International Citation Shares Relative to Home: Citations to High Quality Research

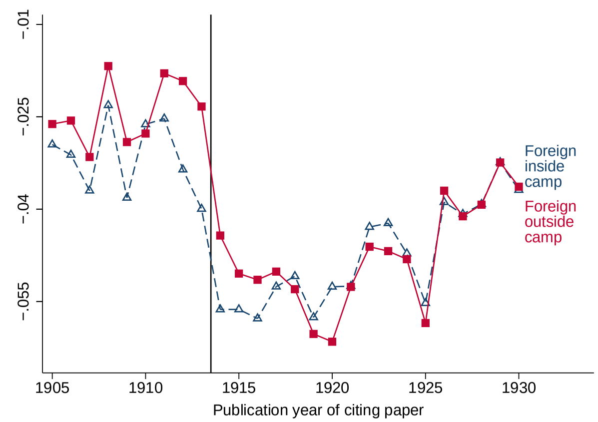
(a) Citations to Top 5% Research



(b) Citations to Top 3% Research



(c) Citations to Top 1% Research

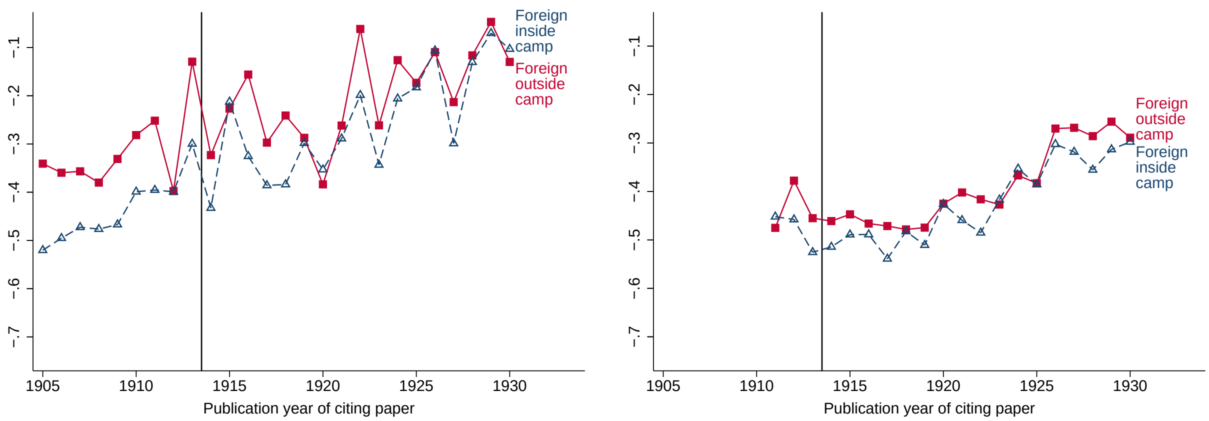


Notes: Each panel plots one set of parameter estimates of the equivalent of regression (2). For the results reported in panel (a), we split citation shares to research from home into research that ended up in the top 5% of the citation distribution and research that ended up in the bottom 95%. Similarly, we split citation shares to research produced inside the camp and outside the camp. The "Foreign outside camp" line measures citation shares to top 5% research from outside the camp, relative to top 5% research from home. The "Foreign inside camp" line measures citation shares to top 5% research from foreign scientists inside the camp, relative to top 5% research from home. The regressions also include the citation shares to non-frontier research from outside the camp, inside the camp, and home. In all panels, we count citations to recent research, i.e. research published in the preceding five years. For example, the first dot (1905) measures relative citation shares to top 5% research published between 1901 and 1905, and so on. Panel (b) reports estimates for changes in citation shares to research that ended up in the top 3% of the citation distribution, and panel (c) reports estimates for changes in citation shares to research that ended up in the top 1% of the citation distribution. The data were collected by the authors and combine scientist census data from *Minerva - Handbuch der Gelehrten Welt* and publication and citation data from *ISI - Web of Science* (see section 2 for details).

Figure VI:
International Citation Shares Relative to Home: Citations to Pre-War Research

(a) Citations to 1903-05 Research

(b) Citations to 1911-13 Research

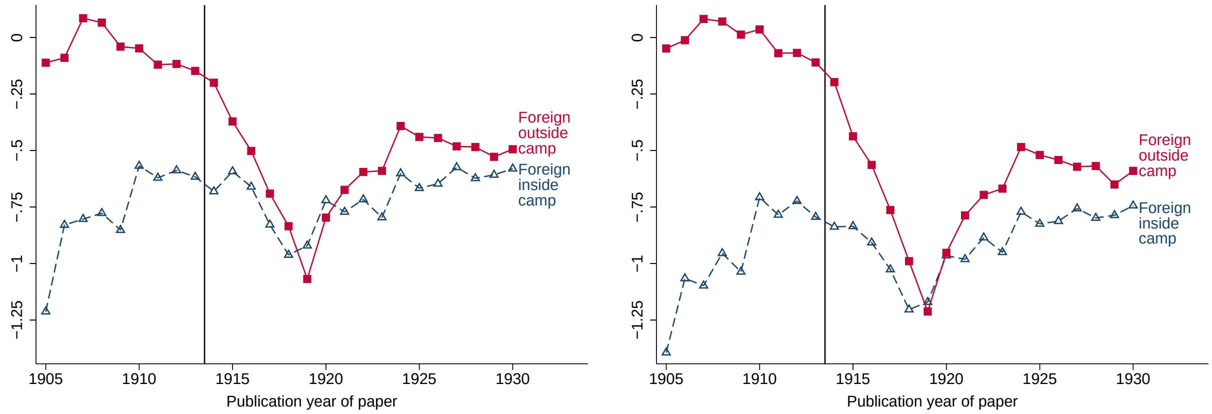


Notes: Each panel plots one set of parameter estimates of regression (2) with citation shares to pre-war research as the dependent variable. Differently from previous figures, each dot of any line measures relative citation shares to a *fixed cohort* of research, published either in 1903-1905 (panel a) or in 1911-1913 (panel b). In panel (a), the "Foreign outside camp" line reports point estimates (ω_τ) that measure citation shares to 1903-1905 research from outside the camp, relative to 1903-1905 research from home. The "Foreign inside camp" line reports point estimates (ι_τ) that measure citation shares to 1903-1905 research from inside the camp, relative to 1903-1905 research from home. Regression results from panel (b) refer to research published in 1911-1913 and can be interpreted similarly. The data were collected by the authors and combine scientist census data from *Minerva - Handbuch der Gelehrten Welt* and publication and citation data from *ISI - Web of Science* (see section 2 for details).

Figure VII:
INTERNATIONAL TITLE SIMILARITY RELATIVE TO HOME

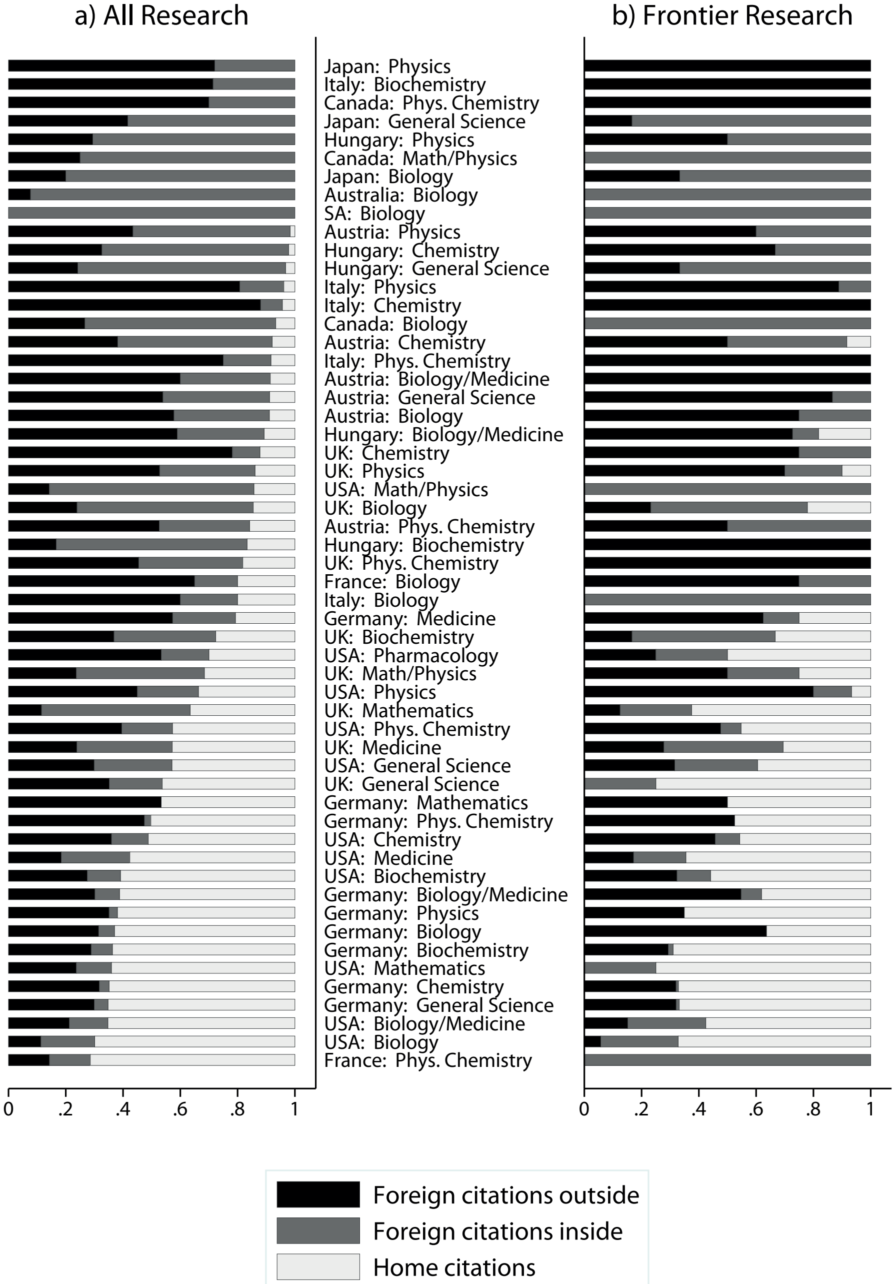
(a) Similarity to Most Similar Title

(b) Average Similarity to 5 Most Similar Titles



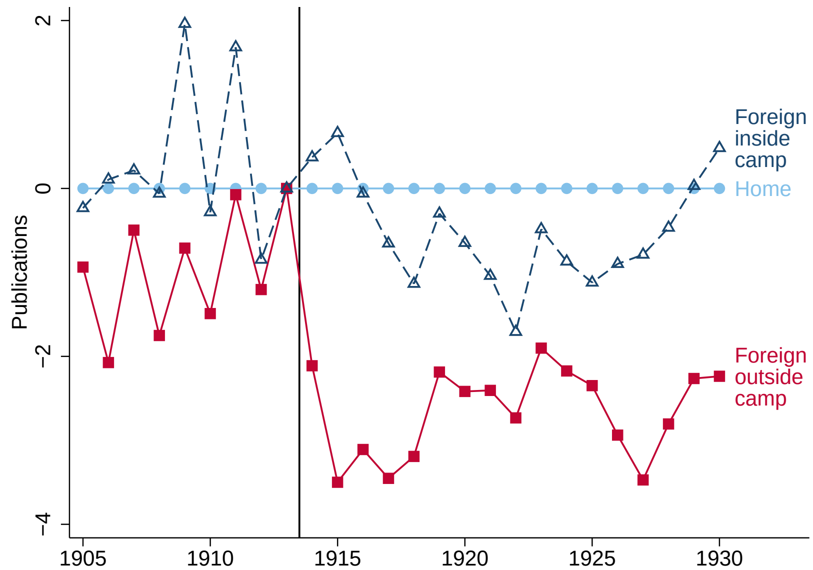
Notes: Each panel plots one set of parameter estimates of the equivalent of regression (2) where the dependent variable measures the standardized (i.e., mean 0 and standard deviation 1) LSA title similarity to papers by scientists from home, foreign countries inside the camp, and foreign countries outside the camp. In panel (a), LSA title similarity is computed as the similarity to the most similar title from each camp. In panel (b), LSA title similarity is computed as the average similarity to the five most similar titles from each camp. The "Foreign outside camp" line reports point estimates (ω_τ) that measure the LSA title similarity to papers from outside the camp, relative to papers from home. The "Foreign inside camp" line reports point estimates (ι_τ) that measure the LSA title similarity to papers from foreign scientists inside the camp, relative to papers from home. We measure title similarity to recent papers, i.e. papers published in the preceding five years. For example, the first dot (1905) measures relative title similarity to papers published between 1901 and 1905, and so on. The data were collected by the authors and combine scientist census data from *Minerva - Handbuch der Gelehrten Welt* and publication and citation data from *ISI - Web of Science* (see section 2 for details).

Figure VIII:
Pre-War Citations to Research from Home, Foreign Inside Camp, and Outside Camp



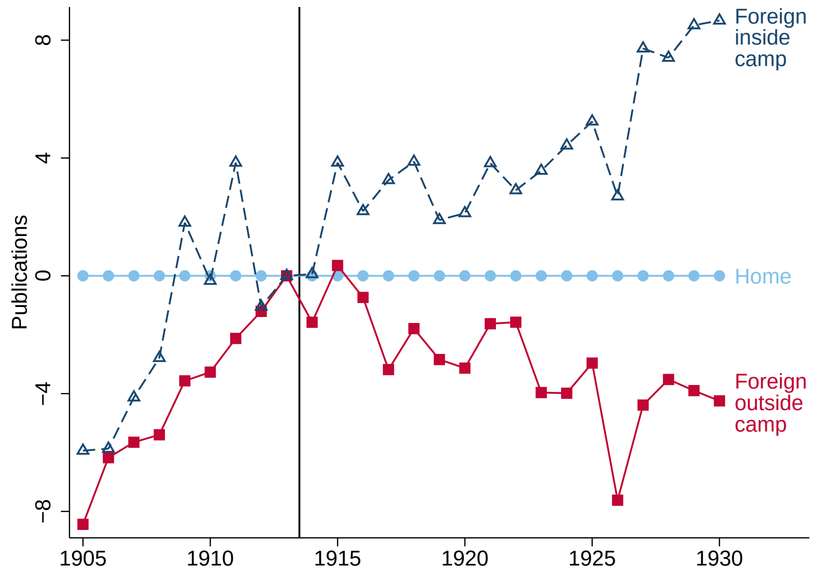
Notes: Panel (a) shows the pre-war reliance on all research (i.e., both frontier and non-frontier) from home, from abroad outside the camp, and from abroad inside the camp for each field-country pair. Pre-war reliance on all research is calculated as the average citation shares to recent research from home, foreign countries inside the camp, and foreign countries outside the camp for all citing papers published by all university scientists in each field-country pair between 1900 to 1913. Panel (b) focuses on pre-war reliance to frontier research, measured as average shares of citations to top 3% research. The data were collected by the authors and combine scientist census data from *Minerva - Handbuch der Gelehrten Welt* and publication and citation data from *ISI - Web of Science* (see section 2 for details).

Figure IX:
EFFECT ON PUBLICATIONS



Notes: The Figure plots parameter estimates from regression (4). The "Foreign outside camp" line reports point estimates ($\beta_{1\tau}$) that measure changes in yearly publications for scientists in field-country pairs that, in the pre-war period, relied on frontier research from outside the camp, compared to scientists who relied on frontier research from home. The "Foreign inside camp" line reports point estimates ($\beta_{2\tau}$) that measure changes in yearly publications for scientists in field-country pairs that, in the pre-war period, relied on frontier research from foreign scientists inside the camp, compared to scientists who relied on frontier research from home. Pre-war reliance on frontier research is measured by pre-war citations to frontier research at the field-country pair level. Frontier research is defined as research that ended up in the top 1% of the subject-level citation distribution, counting citations until today. The regression also controls for pre-war reliance on non-frontier research from each camp interacted with year indicators. The data were collected by the authors and combine scientist census data from *Minerva - Handbuch der Gelehrten Welt* and publication and citation data from *ISI - Web of Science* (see section 2 for details).

Figure X:
EFFECT ON PUBLICATIONS: WITHIN U.S. VARIATION



Notes: The Figure plots parameter estimates from regression (4) when we restrict the sample to scientists based in the United States. The "Foreign outside camp" line reports point estimates ($\beta_{1\tau}$) that measure changes in yearly publications for scientists in field-country pairs that, in the pre-war period, relied on frontier research from outside the camp, compared to scientists who relied on frontier research from home. The "Foreign inside camp" line reports point estimates ($\beta_{2\tau}$) that measure changes in yearly publications for scientists in field-country pairs that, in the pre-war period, relied on frontier research from foreign scientists inside the camp, compared to scientists who relied on frontier research from home. Pre-war reliance on frontier research is measured by pre-war citations to frontier research at the field-country pair level. Frontier research is defined as research that ended up in the top 1% of the subject-level citation distribution, counting citations until today. The regression also controls for pre-war dependence on non-frontier research from each camp interacted with year indicators. The data were collected by the authors and combine scientist census data from *Minerva - Handbuch der Gelehrten Welt* and publication and citation data from *ISI - Web of Science* (see section 2 for details).

Tables

Table I:
Scientific Camps during WWI and the Boycott

Allies	Centrals	Neutrals
U.S.A.	Germany	Switzerland
U.K. (incl. Ireland)	Austria	Netherlands
France	Hungary	Sweden
Canada	Bulgaria	Denmark
Japan	Ottoman E. / Turkey	Norway
Italy		Czechoslovakia
Belgium		Finland
Australia		Spain
Romania		Monaco
Poland		
Brazil		
South Africa		
Greece		
New Zealand		
Portugal		
Serbia		

Notes: The Table reports the countries in each camp during WWI and the boycott. Countries are classified following the definition of the International Research Council (IRC) and ordered by scientific output in our data. Austria-Hungary was split into two countries after WWI. Czechoslovakia was part of Austria-Hungary before WWI and became a sovereign state after 1918. Turkey emerged from parts of the Ottoman Empire after WWI.

Table II:
ATTENDANCE OF INTERNATIONAL CONGRESSES OF MATHEMATICIANS

Year	Location	Delegates from:							
		Germany	Switzerland	France	U.S.A.	Canada	U.K.	Italy	Others
1897	Zurich	53	68	29	7	0	3	25	57
1900	Paris	26	7	93	19	1	12	23	69
1904	Heidelberg	204	13	29	19	1	8	14	108
1908	Rome	174	18	92	27	1	33	213	142
1912	Cambridge (U.K.)	70	10	45	87	5	270	41	181
1916	Stockholm				*Canceled*				
1920	Strasbourg	0	12	112	15	1	11	7	99
1924	Toronto	0	5	45	270	118	93	15	80
1928	Bologna	106	48	91	76	7	64	412	312
1932	Zurich	142	185	89	102	2	49	81	203

Notes: The Table reports the number of delegates at each *International Congress of Mathematicians*. Data were collected by the authors from historical issues of *Proceedings of the International Congresses of Mathematicians* (see Appendix E.2 for details).

Table III:
Summary Statistics: International Citation Shares and LSA Title Similarity

	(1)	(2) Home	(3) Foreign inside camp	(4) Foreign outside camp
Panel A: References				
Quality of references	Aver. num. of cits. to recent research	Average citation shares to recent research		
all references	2.593	0.686	0.159	0.150
top 1% references	0.207	0.054	0.012	0.013
top 3% references	0.479	0.126	0.027	0.029
top 5% references	0.702	0.181	0.041	0.040
Panel B: Standarized LSA Title Similarity				
		Average LSA title similarity to recent papers		
similarity to most similar title		0.376	-0.300	-0.076
avg. similarity to 5 most similar titles		0.462	-0.399	-0.063

Notes: In column (1, panel A), the table reports the number of references to recent papers (published between year *t-4* and *t*, where *t* is the publication year of the citing paper). In columns (2, panel A) to (4, panel A), the table reports citation shares to research from home, foreign countries inside the camp, and foreign countries outside the camp. For top *x%* references, citation shares are computed as the share of all references (both high quality and low quality). In columns (2, panel B) to (4, panel B), the table reports the standardized (i.e., mean 0 and standard deviation 1) LSA title similarity to papers by scientists from home, foreign countries inside the camp, and foreign countries outside the camp. In the penultimate row, LSA title similarity is computed as the similarity to the most similar title from each camp. In the last row, LSA title similarity is computed as the average similarity to the five most similar titles from each camp. We compute title similarity to recent papers (published between year *t-4* and *t*). The data were collected by the authors and combine scientist census data from *Minerva - Handbuch der Gelehrten Welt* and publication and citation data from *ISI - Web of Science* (see section 2 for details).

Table IV:
CHANGES IN INTERNATIONAL CITATIONS

Dependent variable: *Citation Shares to recent research*	(1)	(2)	(3)	(4)
Foreign *outside* camp × Post 1914	-0.217***	-0.261***		
	(0.033)	(0.040)		
Foreign *outside* camp × WWI			-0.222***	-0.229***
			(0.025)	(0.034)
Foreign *outside* camp × Boycott			-0.245***	-0.258***
			(0.034)	(0.052)
Foreign *outside* camp × Post Boycott			-0.194***	-0.213***
			(0.042)	(0.051)
Foreign *inside* camp × Post 1914	-0.072*	-0.155***		
	(0.041)	(0.051)		
Foreign *inside* camp × WWI			-0.111***	-0.148***
			(0.040)	(0.045)
Foreign *inside* camp × Boycott			-0.089**	-0.164***
			(0.042)	(0.057)
Foreign *inside* camp × Post Boycott			-0.048	-0.154**
			(0.048)	(0.059)
Paper FE	YES	YES	YES	YES
Camp FE	YES	YES	YES	YES
Foreign *in/outside* time trends		YES		YES
Observations	105,378	105,378	105,378	105,378
Number of citing papers	35,126	35,126	35,126	35,126
Within R-squared	0.334	0.335	0.335	0.335

Notes: Each column reports one set of parameter estimates of regression (1) for citing papers published between 1905 and 1930. The dependent variable measures citation shares to research by scientists from home, foreign countries inside the camp, and foreign countries outside the camp. We count citations to recent research, i.e. research published in the preceding five years, e.g. 1901-1905 for citing papers published in 1905, 1902-1906 for citing papers published in 1906, and so on. The reference/omitted category is the citation share to research from home. Standard errors are clustered at the country-times-field level. Significance levels: $***$ p<0.01, $**$ p<0.05, and $*$ p<0.1. The data were collected by the authors and combine scientist census data from *Minerva - Handbuch der Gelehrten Welt* and publication and citation data from *ISI - Web of Science* (see section 2 for details).

Table V:
Changes in International Citations: Frontier Research

Dependent variable:	(1)	(2)	(3)	(4)	(5)	(6)
Cit. Sh. to recent frontier research	Frontier: 5%		Frontier: 3%		Frontier: 1%	
Foreign *outside* camp × Post 1914	-0.053***	-0.097***	-0.035***	-0.066***	-0.021***	-0.039***
	(0.017)	(0.021)	(0.013)	(0.013)	(0.006)	(0.007)
Foreign *inside* camp × Post 1914	-0.023	-0.071***	-0.019*	-0.049***	-0.013**	-0.033***
	(0.015)	(0.021)	(0.011)	(0.013)	(0.006)	(0.007)
Paper FE	YES	YES	YES	YES	YES	YES
Camp FE	YES	YES	YES	YES	YES	YES
Non-frontier research interactions	YES	YES	YES	YES	YES	YES
Foreign *in/outside* time trends		YES		YES		YES
Observations	210,756	210,756	210,756	210,756	210,756	210,756
Number of citing papers	35,126	35,126	35,126	35,126	35,126	35,126
Within R-squared	0.235	0.235	0.299	0.300	0.400	0.400

Notes: Each column reports one set of parameter estimates of regression (1) for citing papers published between 1905 and 1930. The dependent variable measures citation shares to frontier and non-frontier research by scientists from home, foreign countries inside the camp, and foreign countries outside the camp, i.e. six shares for each citing paper. The Table only reports estimates for frontier research, although the regressions control for non-frontier times post-1914 indicators. For the results reported in columns (1)-(2), frontier research is defined as research that ended up in the top 5% of the subject-level citation distribution, counting citations until today. Similarly, for the results reported in columns (3)-(4) (and (5)-(6)), frontier research is defined as research that ended up in the top 3% (and 1%) of the subject-level citation distribution. We count citations to recent research, i.e. research published in the preceding five years, e.g. 1901-1905 for citing papers published in 1905, 1902-1906 for citing papers published in 1906, and so on. The reference/omitted category is the citation share to frontier research from home. Standard errors are clustered at the country-times-field level. Significance levels: $***$ p<0.01, $**$ p<0.05, and $*$ p<0.1. The data were collected by the authors and combine scientist census data from *Minerva - Handbuch der Gelehrten Welt* and publication and citation data from *ISI - Web of Science* (see section 2 for details).

Table VI:
THE SIMILARITY OF PAPERS AS MEASURED BY LATENT SEMANTIC ANALYSIS

Dependent variable:	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
LSA Title Similarity to recent papers	Most similar title				Average 5 most similar titles			
Foreign *outside* camp × Post 1914	-0.467***	-0.557***			-0.608***	-0.678***		
	(0.095)	(0.126)			(0.131)	(0.165)		
Foreign *outside* camp × WWI			-0.459***	-0.517***			-0.575***	-0.639***
			(0.084)	(0.117)			(0.118)	(0.143)
Foreign *outside* camp × Boycott			-0.530***	-0.648***			-0.678***	-0.806***
			(0.111)	(0.193)			(0.150)	(0.213)
Foreign *outside* camp × Post Boycott			-0.426***	-0.593***			-0.569***	-0.753***
			(0.099)	(0.188)			(0.134)	(0.192)
Foreign *inside* camp × Post 1914	0.060	-0.164			0.058	-0.226		
	(0.151)	(0.140)			(0.191)	(0.178)		
Foreign *inside* camp × WWI			-0.019	-0.181			-0.054	-0.267*
			(0.137)	(0.117)			(0.177)	(0.141)
Foreign *inside* camp × Boycott			0.006	-0.320**			0.005	-0.425***
			(0.161)	(0.152)			(0.202)	(0.160)
Foreign *inside* camp × Post Boycott			0.122	-0.343**			0.131	-0.482***
			(0.154)	(0.165)			(0.194)	(0.165)
Paper FE	YES	YES	YES	YES	YES	YES	YES	YES
Camp FE	YES	YES	YES	YES	YES	YES	YES	YES
Foreign *in/outside* time trends		YES		YES		YES		YES
Observations	71,586	71,586	71,586	71,586	71,586	71,586	71,586	71,586
Number of citing papers	23,862	23,862	23,862	23,862	23,862	23,862	23,862	23,862
Within R-squared	0.156	0.157	0.157	0.158	0.225	0.228	0.227	0.228

Notes: Each column reports one set of parameter estimates of regression (1) for papers published between 1905 and 1930. The dependent variable measures the standardized (i.e., mean 0 and standard deviation 1) LSA title similarity to papers by scientists from home, foreign countries inside the camp, and foreign countries outside the camp. In columns (1) to (4), LSA title similarity is computed as the similarity to the most similar paper from each camp. In columns (5) to (8), LSA title similarity is computed as the average similarity to the five most similar papers from each camp. We compute title similarity to recent papers, i.e. papers published in the preceding five years, e.g. 1901-1905 for papers published in 1905. The reference/omitted category is the LSA title similarity to papers from home. Standard errors are clustered at the country-times-field level. Significance levels: $***$ p<0.01, $**$ p<0.05, and $*$ p<0.1. The data were collected by the authors and combine scientist census data from *Minerva - Handbuch der Gelehrten Welt* and publication and citation data from *ISI - Web of Science* (see section 2 for details).

Table VII:
SUMMARY STATISTICS: PRODUCTIVITY OF SCIENTISTS

	Mean	Std. Dev.
Number of scientists	8,734	
Number of scientist-year observations	227,084	
Career age in years	7.444	7.708
Publications per year	0.267	0.950
Nobel-nominated papers per year	0.001	0.029
Nomination weighted Nobel-nominated papers per year	0.003	0.152
Number of novel words (word innovation) per year	0.042	0.273
Patent relevant word innovation per year	0.427	3.538

Notes: The Table reports summary statistics for the panel of scientists with a university position by 1914. The data were collected by the authors and combine scientist census data from *Minerva - Handbuch der Gelehrten Welt*, publication and citation data from *ISI - Web of Science*, Nobel nomination and award data from Nobelprize.org (2014), and patent data from *U.S. Patent Office* (see section 2 for details).

Table VIII:
Effect on Publications

Dependent variable: *Number of publications*	(1) Frontier: 1%	(2) Frontier: 3%	(3) Frontier: 5%
Pre-war reliance on frontier *OUT* × Post 1914	-1.727***	-0.784***	-0.380*
	(0.638)	(0.282)	(0.220)
Pre-war reliance on frontier *IN* × Post 1914	-0.827	-0.363	-0.152
	(0.736)	(0.283)	(0.218)
Scientist FE	YES	YES	YES
Year FE	YES	YES	YES
Pre-war reliance on non-frontier	YES	YES	YES
Career age × field interactions	YES	YES	YES
Observations	227,084	227,084	227,084
Number of scientists	8,734	8,734	8,734
Within R-squared	0.062	0.062	0.062

Notes: Each column reports one set of parameter estimates of regression (3) for the panel of university scientists. The dependent variable measures the yearly number of publications in the 160 top journals in our data for the years 1905 to 1930. The number of publications is normalized by the number of authors and standardized to mean zero and standard deviation one within fields. "Pre-war reliance on frontier *OUT*" is the pre-war citation share to frontier research (1%, 3%, or 5%) from outside the camp. "Pre-war reliance on frontier *IN*" is the pre-war citation share to frontier research (1%, 3%, or 5%) from foreign countries inside the camp. The reference/omitted category is "Pre-war reliance on frontier *HOME*." Standard errors are clustered at the country-times-field level. Significance levels: ∗∗∗ p<0.01, ∗∗ p<0.05, and ∗ p<0.1. The data were collected by the authors and combine scientist census data from *Minerva - Handbuch der Gelehrten Welt* and publication and citation data from *ISI - Web of Science* (see section 2 for details).

Table IX:
EFFECT ON PUBLICATIONS: ROBUSTNESS CHECKS

Dependent variable: *Number of publications*	(1) # pub. per author	(2) # pub. not normal. by # authors	(3) Control for camp × year	(4) Control for field × year	(5) Control for camp × field × year
Panel A: Frontier measured by Top 1%					
Pre-war reliance on 1% frontier *OUT*	-1.727***	-1.775**	-1.489*	-1.655***	-1.667***
× Post 1914	(0.638)	(0.669)	(0.826)	(0.616)	(0.491)
Pre-war reliance on 1% frontier *IN*	-0.827	-0.923	-0.823	-0.782	-0.762
× Post 1914	(0.736)	(0.730)	(0.764)	(0.725)	(0.698)
Within R-squared	0.062	0.066	0.064	0.064	0.068
Panel B: Frontier measured by Top 3%					
Pre-war reliance on 3% frontier *OUT*	-0.784***	-0.813***	-0.596	-0.744**	-1.105***
× Post 1914	(0.282)	(0.288)	(0.379)	(0.295)	(0.237)
Pre-war reliance on 3% frontier *IN*	-0.363	-0.454	-0.432	-0.300	-0.311
× Post 1914	(0.283)	(0.279)	(0.297)	(0.292)	(0.265)
Within R-squared	0.062	0.066	0.063	0.064	0.068
Panel C: Frontier measured by Top 5%					
Pre-war reliance on 5% frontier *OUT*	-0.380*	-0.400*	-0.224	-0.372	-0.686***
× Post 1914	(0.220)	(0.222)	(0.262)	(0.270)	(0.256)
Pre-war reliance on 5% frontier *IN*	-0.152	-0.205	-0.170	-0.120	-0.167
× Post 1914	(0.218)	(0.218)	(0.225)	(0.230)	(0.192)
Within R-squared	0.062	0.066	0.063	0.064	0.068
Scientist FE	YES	YES	YES	YES	YES
Year FE	YES	YES			
Pre-war reliance on non-frontier	YES	YES	YES	YES	YES
Career age × field interactions	YES	YES	YES	YES	YES
Camp × year FE			YES		
Field × year FE				YES	
Camp × field × year FE					YES
Observations	227,084	227,084	227,084	227,084	227,084
Number of scientists	8,734	8,734	8,734	8,734	8,734

Notes: Each column and each panel reports one set of parameter estimates of regression (3) for the panel of university scientists. For the results presented in Panel A (B and C) we measure the frontier as the top 1% (top 3% and top 5%) research. The dependent variable measures the yearly number of publications in the 160 top journals in our data for the years 1905 to 1930. In column (1) and (3)-(5), the dependent variable is normalized by the number of authors and standardized to mean zero and standard deviation one within fields. In column (2), the dependent variable is not normalized by the number of authors but standardized to mean zero and standard deviation one within fields. "Pre-war reliance on frontier *OUT*" is the pre-war citation share to frontier research (1%, 3%, or 5%) from outside the camp. "Pre-war reliance on frontier *IN*" is the pre-war citation share to frontier research (1%, 3%, or 5%) from foreign countries inside the camp. The reference/omitted category is "Pre-war reliance on frontier *HOME*." Standard errors are clustered at the country-times-field level. Significance levels: *** p<0.01, ** p<0.05, and * p<0.1. The data were collected by the authors and combine scientist census data from *Minerva - Handbuch der Gelehrten Welt* and publication and citation data from *ISI - Web of Science* (see section 2 for details).

Table X:
Effect on Publications: Disruption of Knowledge Flows or Other War Related Disruption?

Dependent variable: *Number of publications*	(1) Control for combat in country	(2) Control for total deaths per capita	(3) Control for civilian deaths per capita	(4) Control for (2), (3), and (4)	(5) Exclude chemistry	(6) # pub. in own-camp journals
Panel A: Frontier measured by Top 1%						
Pre-war reliance on 1% frontier *OUT*	-1.846***	-1.547***	-1.987***	-1.649***	-1.721***	-1.484**
× Post 1914	(0.527)	(0.414)	(0.433)	(0.385)	(0.563)	(0.639)
Pre-war reliance on 1% frontier *IN*	-0.739	-0.351	-0.489	-0.248	-0.653	-0.545
× Post 1914	(0.731)	(0.742)	(0.690)	(0.666)	(0.740)	(0.707)
Within R-squared	0.068	0.068	0.068	0.069	0.069	0.068
Pre-war reliance on 3% frontier *OUT*	-1.158***	-0.984***	-1.297***	-1.056***	-1.142***	-1.074***
× Post 1914	(0.232)	(0.241)	(0.179)	(0.195)	(0.271)	(0.314)
Pre-war reliance on 3% frontier *IN*	-0.297	0.024	-0.109	0.089	-0.281	-0.214
× Post 1914	(0.272)	(0.312)	(0.268)	(0.278)	(0.281)	(0.301)
Within R-squared	0.068	0.068	0.068	0.069	0.069	0.068
Pre-war reliance on 5% frontier *OUT*	-0.663**	-0.625**	-0.888***	-0.676**	-0.632**	-0.566*
× Post 1914	(0.280)	(0.270)	(0.221)	(0.266)	(0.296)	(0.339)
Pre-war reliance on 5% frontier *IN*	-0.176	-0.098	-0.061	-0.086	-0.060	-0.078
× Post 1914	(0.191)	(0.205)	(0.177)	(0.189)	(0.202)	(0.212)
Within R-squared	0.068	0.068	0.068	0.068	0.069	0.068
Scientist FE	YES	YES	YES	YES	YES	YES
Pre-war reliance on non-frontier	YES	YES	YES	YES	YES	YES
Career age × field interactions	YES	YES	YES	YES	YES	YES
Camp × field × year FE	YES	YES	YES	YES	YES	YES
Observations	227,084	227,084	227,084	227,084	197,782	215,046
Number of scientists	8,734	8,734	8,734	8,734	7,607	8,271

Notes: Each column and each panel reports one set of parameter estimates of regression (3) for the panel of university scientists. In columns (1)-(5), the dependent variable measures the yearly number of publications in all 160 top journals in our data in the years 1905 to 1930. In column (6), the dependent variable measures the yearly number of publications in own-camp journals in our data in the years 1905 to 1930. In all columns, the dependent variable is normalized by the number of authors and standardized to mean zero and standard deviation one within fields. "Pre-war reliance on frontier *OUT*" is the pre-war citation share to frontier research (1%, 3%, or 5%) from outside the camp. "Pre-war reliance on frontier *IN*" is the pre-war citation share to frontier research (1%, 3%, or 5%) from foreign countries inside the camp. The reference/omitted category is "Pre-war reliance on frontier *HOME*." Standard errors are clustered at the country-times-field level. Significance levels: ∗∗∗ p<0.01, ∗∗ p<0.05, and ∗ p<0.1. The data were collected by the authors and combine: scientist census data from *Minerva - Handbuch der Gelehrten Welt*, publication and citation data from *ISI - Web of Science*, and war intensity data from Mouguel (2011), *1914-1918 online: International Encyclopedia of the First World War*, and *Wikipedia* (see section 2 and Appendix E.5 for details).

Table XI:
Effect on Nobel-Nominated Papers

	(1)	(2)	(3)	(4)
Dependent Variable:	Nomination paper		Nomination paper weighted by # noms.	
Panel A: Frontier measured by Top 1%				
Pre-war reliance on 1% frontier *OUT*	-0.021**	-0.019*	-0.148***	-0.175*
× Post 1914	(0.008)	(0.011)	(0.052)	(0.103)
Pre-war reliance on 1% frontier *IN*	-0.005	-0.003	-0.048	-0.033
× Post 1914	(0.008)	(0.009)	(0.041)	(0.062)
Within R-squared	0.001	0.005	0.001	0.004
Panel B: Frontier measured by Top 3%				
Pre-war reliance on 3% frontier *OUT*	-0.012***	-0.012***	-0.061**	-0.073
× Post 1914	(0.004)	(0.004)	(0.028)	(0.045)
Pre-war reliance on 3% frontier *IN*	-0.005	-0.006	-0.021	-0.011
× Post 1914	(0.004)	(0.005)	(0.018)	(0.020)
Within R-squared	0.001	0.005	0.001	0.004
Panel C: Frontier measured by Top 5%				
Pre-war reliance on 5% frontier *OUT*	-0.010**	-0.010**	-0.072**	-0.074**
× Post 1914	(0.004)	(0.004)	(0.027)	(0.030)
Pre-war reliance on 5% frontier *IN*	-0.002	-0.003	0.012	0.020
× Post 1914	(0.003)	(0.003)	(0.017)	(0.019)
Within R-squared	0.001	0.005	0.001	0.004
Scientist FE	YES	YES	YES	YES
Year FE	YES		YES	
Pre-war reliance on non-frontier	YES	YES	YES	YES
Career age × field interactions	YES	YES	YES	YES
Camp × field × year FE		YES		YES
Observations	227,084	227,084	227,084	227,084
Number of scientists	8,734	8,734	8,734	8,734

Notes: Each column and each panel reports one set of parameter estimates of regression (3) for the panel of university scientists. The dependent variable in columns (1) and (2) is an indicator that equals one if a scientist published a Nobel-nominated paper in a certain year between 1905 and 1930, and zero for all other years. The dependent variable in columns (3) and (4) weighs the Nobel-nominated paper indicator by the number of nominations in the two years before a candidate's last nomination. "Pre-war reliance on frontier *OUT*" is the pre-war citation share to frontier research (1%, 3%, or 5%) from outside the camp. "Pre-war reliance on frontier *IN*" is the pre-war citation share to frontier research (1%, 3%, or 5%) from foreign countries inside the camp. The reference/omitted category is "Pre-war reliance on frontier *HOME*." Standard errors are clustered at the country-times-field level. Significance levels: *** p<0.01, ** p<0.05, and * p<0.1. The data were collected by the authors and combine scientist census data from *Minerva - Handbuch der Gelehrten Welt*, publication and citation data from *ISI - Web of Science*, and Nobel nomination and award data from Nobelprize.org (2014) (see section 2 for details).

Table XII:
EFFECT ON WORD INNOVATION AND PATENTS

	(1)	(2)	(3)	(4)
Dependent Variable:	Novel scientific words		Patent-relevant words	
Panel A: Frontier measured by Top 1%				
Pre-war reliance on 1% frontier *OUT*	-1.229***	-0.778**	-1.134***	-1.207***
× Post 1914	(0.441)	(0.327)	(0.349)	(0.297)
Pre-war reliance on 1% frontier *IN*	-0.910*	-0.918**	-0.569*	-0.661**
× Post 1914	(0.468)	(0.368)	(0.295)	(0.253)
Within R-squared	0.025	0.028	0.015	0.018
Panel B: Frontier measured by Top 3%				
Pre-war reliance on 3% frontier *OUT*	-0.311	-0.359**	-0.415**	-0.639***
× Post 1914	(0.261)	(0.173)	(0.198)	(0.155)
Pre-war reliance on 3% frontier *IN*	-0.149	-0.181	-0.115	-0.129
× Post 1914	(0.225)	(0.167)	(0.182)	(0.139)
Within R-squared	0.024	0.028	0.015	0.018
Panel C: Frontier measured by Top 5%				
Pre-war reliance on 5% frontier *OUT*	-0.182	-0.298*	-0.339**	-0.542***
× Post 1914	(0.204)	(0.164)	(0.158)	(0.149)
Pre-war reliance on 5% frontier *IN*	-0.149	-0.150	-0.136	-0.161
× Post 1914	(0.173)	(0.134)	(0.134)	(0.102)
Within R-squared	0.024	0.028	0.015	0.018
Scientist FE	YES	YES	YES	YES
Year FE	YES		YES	
Pre-war reliance on non-frontier	YES	YES	YES	YES
Career age × field interactions	YES	YES	YES	YES
Camp × field × year FE		YES		YES
Observations	227,084	227,084	227,084	227,084
Number of scientists	8,734	8,734	8,734	8,734

Notes: Each column and each panel reports one set of parameter estimates of regression (3) for the panel of university scientists. The dependent variable in columns (1) and (2) counts the number of novel words that appeared in the title of a scientific paper published in year *t*. The dependent variable in columns (3) and (4) counts the number of times each of the novel words (as defined above) was used in the text of any patent granted by the U.S. Patent Office in years *t+15* and *t+30*. The dependent variable in columns (3) and (4) is winsorized at the 99th percentile. "Pre-war reliance on frontier *OUT*" is the pre-war citation share to frontier research (1%, 3%, or 5%) from outside the camp. "Pre-war reliance on frontier *IN*" is the pre-war citation share to frontier research (1%, 3%, or 5%) from foreign countries inside the camp. The reference/omitted category is "Pre-war reliance on frontier *HOME*." Standard errors are clustered at the country-times-field level. Significance levels: ∗∗∗ p<0.01, ∗∗ p<0.05, and ∗ p<0.1. The data were collected by the authors and combine scientist census data from *Minerva - Handbuch der Gelehrten Welt*, publication and citation data from *ISI - Web of Science*, Nobel nomination and award data from Nobelprize.org (2014), and patent data from the *U.S. Patent Office* (see section 2 for details).

Table XIII: Effect on Productivity by Pre-War Quality of Scientists

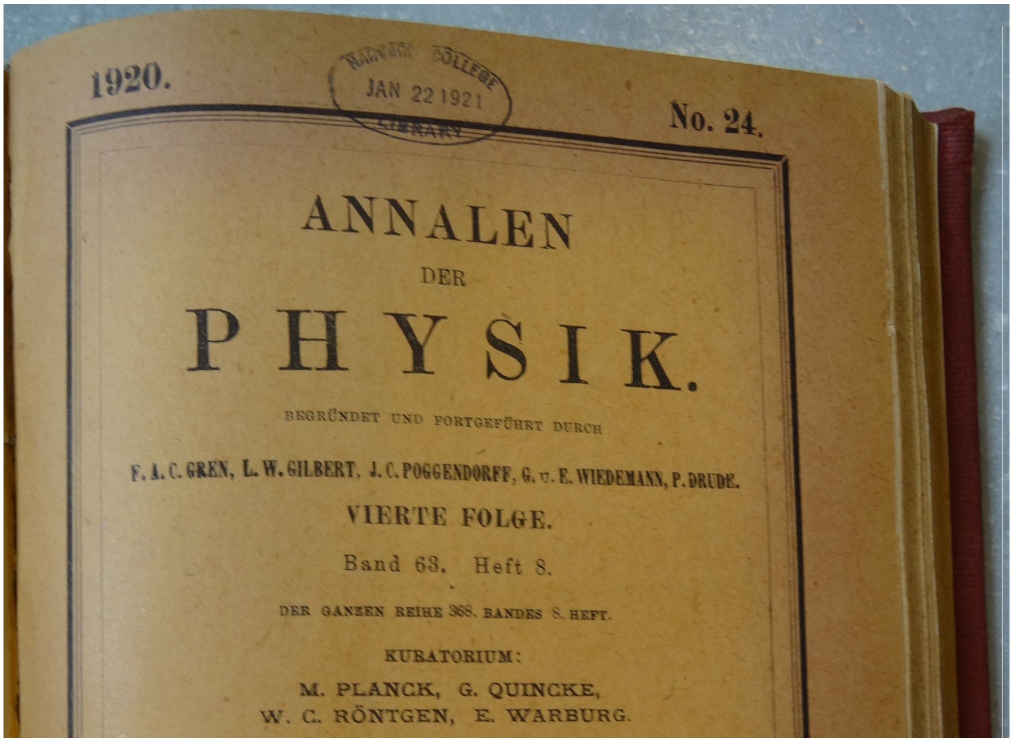
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
	≤ median	>median	≤ median	>median	≤ median	>median	≤ median	>median	≤ median	>median
Dependent Variable:	Number of publications		Nomination paper		Nom. paper (weighted)		Novel scientific words		Patent relevant words	
Panel A: Frontier measured by Top 1%										
Pre-war reliance on 1% frontier *OUT*	-0.430*	-3.295***	0.004	-0.052**	-0.023	-0.373*	-0.149	-1.656**	-0.465***	-2.163***
× Post 1914	(0.227)	(1.237)	(0.007)	(0.022)	(0.039)	(0.219)	(0.099)	(0.778)	(0.135)	(0.714)
Pre-war reliance on 1% frontier *IN*	0.028	-1.693	-0.000	-0.010	-0.004	-0.083	0.026	-1.884***	-0.134	-1.148*
× Post 1914	(0.500)	(1.046)	(0.006)	(0.017)	(0.030)	(0.125)	(0.167)	(0.528)	(0.187)	(0.587)
Within R-squared	0.124	0.077	0.008	0.009	0.016	0.006	0.025	0.046	0.014	0.031
Panel B: Frontier measured by Top 3%										
Pre-war reliance on 3% frontier *OUT*	-0.278**	-2.131***	0.001	-0.031***	-0.004	-0.166	-0.164***	-0.540	-0.327***	-0.992***
× Post 1914	(0.120)	(0.569)	(0.002)	(0.011)	(0.013)	(0.100)	(0.056)	(0.347)	(0.072)	(0.300)
Pre-war reliance on 3% frontier *IN*	-0.088	-0.668	-0.001	-0.012	-0.004	-0.016	-0.037	-0.421	-0.136	-0.125
× Post 1914	(0.182)	(0.438)	(0.003)	(0.008)	(0.013)	(0.034)	(0.073)	(0.294)	(0.096)	(0.290)
Within R-squared	0.124	0.077	0.008	0.009	0.016	0.006	0.025	0.046	0.014	0.031
Panel C: Frontier measured by Top 5%										
Pre-war reliance on 5% frontier *OUT*	-0.070	-1.286***	-0.001	-0.024**	-0.023	-0.142**	-0.140**	-0.295	-0.290***	-0.714***
× Post 1914	(0.167)	(0.454)	(0.003)	(0.010)	(0.015)	(0.065)	(0.067)	(0.306)	(0.079)	(0.266)
Pre-war reliance on 5% frontier *IN*	-0.057	-0.392	-0.000	-0.008	0.001	0.036	-0.057	-0.335	-0.151**	-0.214
× Post 1914	(0.150)	(0.293)	(0.002)	(0.005)	(0.010)	(0.036)	(0.055)	(0.214)	(0.064)	(0.178)
Within R-squared	0.124	0.077	0.008	0.009	0.016	0.006	0.025	0.046	0.014	0.031
Scientist FE	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Pre-war reliance on non-frontier	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Career age × field	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Camp × field × year FE	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Observations	121,446	105,638	121,446	105,638	121,446	105,638	121,446	105,638	121,446	105,638
Number of scientists	4,671	4,063	4,671	4,063	4,671	4,063	4,671	4,063	4,671	4,063

Notes: Each column and each panel reports one set of parameter estimates of regression (3) for the panel of university scientists. We divide the sample of scientists into two sub-samples: scientists who published less or the same number of papers than the median scientist (results reported in odd columns) and scientists who published more papers than the median scientist (even columns). The median number of papers is calculated at the field level for the period 1905-1913. The dependent variables are defined as in the previous tables. "Pre-war reliance on frontier *OUT*" is the pre-war citation share to frontier research (1%, 3%, or 5%) from outside the camp. "Pre-war reliance on frontier *IN*" is the pre-war citation share to frontier research (1%, 3%, or 5%) from foreign countries inside the camp. The reference/omitted category is "Pre-war reliance on frontier *HOME*." Standard errors are clustered at the country-times-field level. Significance levels: *** p<0.01, ** p<0.05, and * p<0.1. The data were collected by the authors and combine scientist census data from *Minerva - Handbuch der Gelehrten Welt*, publication and citation data from *ISI - Web of Science*, Nobel and patent data from the *U.S. Patent Office* (see section 2 for details).

A Appendix Tables and Figures

A.1 Appendix Figures

Figure A.1:
EXAMPLE OF ENTRY STAMP FROM HARVARD LIBRARY


1920. JAN 22 1921 No. 24.

ANNALEN
DER
PHYSIK.

BEGRÜNDET UND FORTGEFÜHRT DURCH
F. A. C. GREN, L. W. GILBERT, J. C. POGGENDORFF, G. u. E. WIEDEMANN, P. DRUDE.

VIERTE FOLGE.

Band 63. Heft 8.

DER GANZEN REIHE 368. BANDES 8. HEFT.

KURATORIUM:
M. PLANCK, G. QUINCKE,
W. C. RÖNTGEN, E. WARBURG.

Notes: The stamp at the top of the page indicates the arrival date of this issue of the *Annalen der Physik* at the Harvard library.

Figure A.2:
Sample page of Minerva

Cambridge (Massachusetts, Ver. St. A.).
HARVARD UNIVERSITY (1636).

Geschichte. Verfassung, Organisation, Aufnahme, Grade, Gebühren: .
Jahreshaushalt. Vermögen nach d. Ausweis von 1912: $ 25 752 720.39. Privatschenkungen 1912: $ 932 409.21 nebst $ 771 772.20 zum sofortigen Gebrauch. Gesamteinnahmen einschliessl. »gifts for immediate use« (1911/12): $ 2 930 752.89, Gesamtausgaben $ 2 503 658.03, Ausgaben für Unterrichtszwecke (Gehälter, usw.) $ 1 292 344.28; Stipendien u. Preise, usw. $ 192 001.81.
Beginn d. akad. Jahres: 22. September, Schluss: 18. Juni.
Zahl der Lehrer (1912/13): 774; der Studierenden: 4279 (College 2308, Graduate Schools 595, Graduate School of Business Administration 107, Divinity School 48, Law School 741, Med. School 290, Dental School 190); dazu 9 Extension Students und 1187 Summer School 1912, ab doppelt gezählt 251 = Summe 5224. — *President:* Abbott Lawrence Lowell. — *Secretaries to the Corporation:* G. Peabody Gardner, jr.; Francis Welles Hunnewell; William Phillips.

— Professors:
Charles S. Sargent: *Baumkult.*
Edward Charles Pickering: *Praktische Astronomie.*
William Gilson Farlow: *Botanik der Kryptogamen.*
Edw. Young Hincks: *Bibl. Theol.*
William Henry Ryder: *Neues Testament.*
Edward H. Bradford: *Orthop. Chirurgie* (Dean of the Faculty of Medicine and of the Medical School).
Joseph D. Brannan: *Rechtswiss.*
Charles A. Brackett: *Zahnpath.*
Thomas M. Rotch: *Kinderheilk.*
Ephr. Emerton: *Kirchengesch.*
Charles R. Lanman: *Sanskrit.*
Edward Laurens Mark: *Anat.*
Eugene H. Smith: *Zahntechnik* (Dean of the Dental School).
Charles S. Minot: *Vergl. Anat.*
George F. Moore: *Gesch. d. Rel.*
Edward S. Sheldon: *Rom. Phil.*
Horatio Stevens White: *Deutsch.*
Robert W. Willson: *Astronom.*
Charles M. Green: *Geburtshilfe.*
Edward Dyer Peters: *Metallurg.*
Edward Cornelius Briggs: *Zahn-Materia medica und Therapie.*
Le Baron Russell Briggs: *Rhetorik u. Beredsamkeit* (Dean of the Faculty of Arts and Sciences).
William Thomas Councilman: *Pathologische Anatomie.*
Kuno Francke: *German. Kulturgeschichte.*
Edwin Herbert Hall: *Physik.*
David Gordon Lyon: *Hebräisch und andere oriental. Sprachen.*
George H. Monks: *Mund-Chirur.*
Josiah Royce: *Gesch. d. Philos.*
Myles Standish: *Ophthalmolog.*
Harold Clarence Ernst: *Bakter.*
Benjamin Osgood Peirce: *Mathematik und Naturphilosophie.*

Notes: A sample page from *Minerva - Handbuch der Gelehrten Welt* (see section 2 for details).

Figure A.3:
The World of Science in 1914

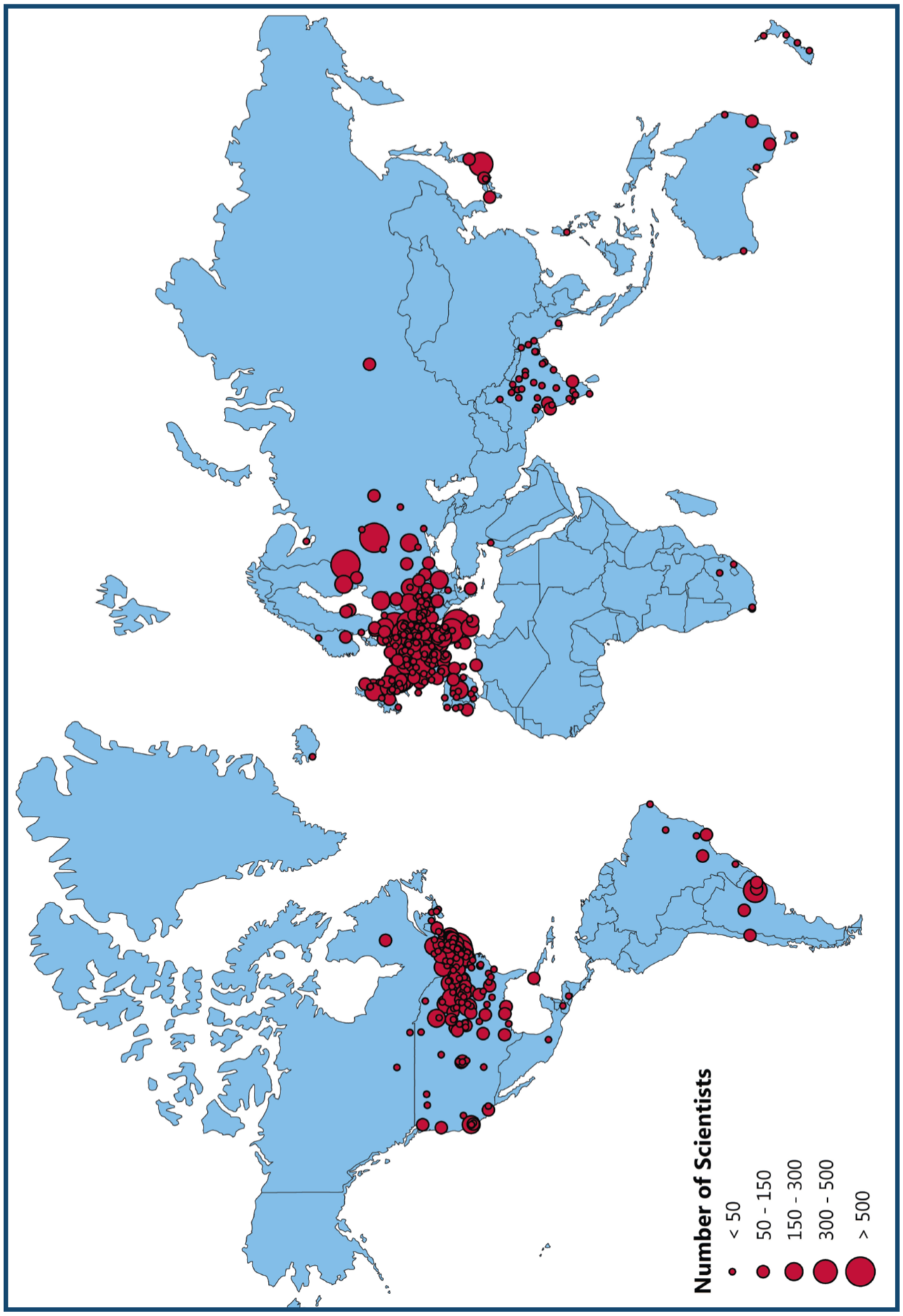
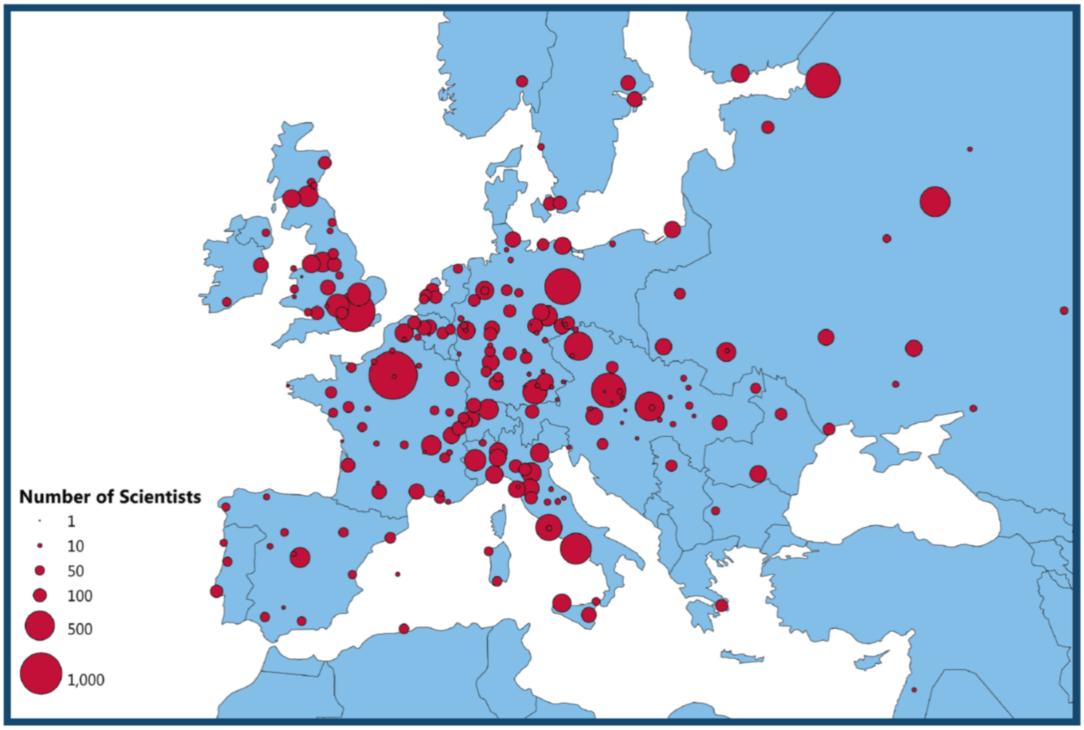
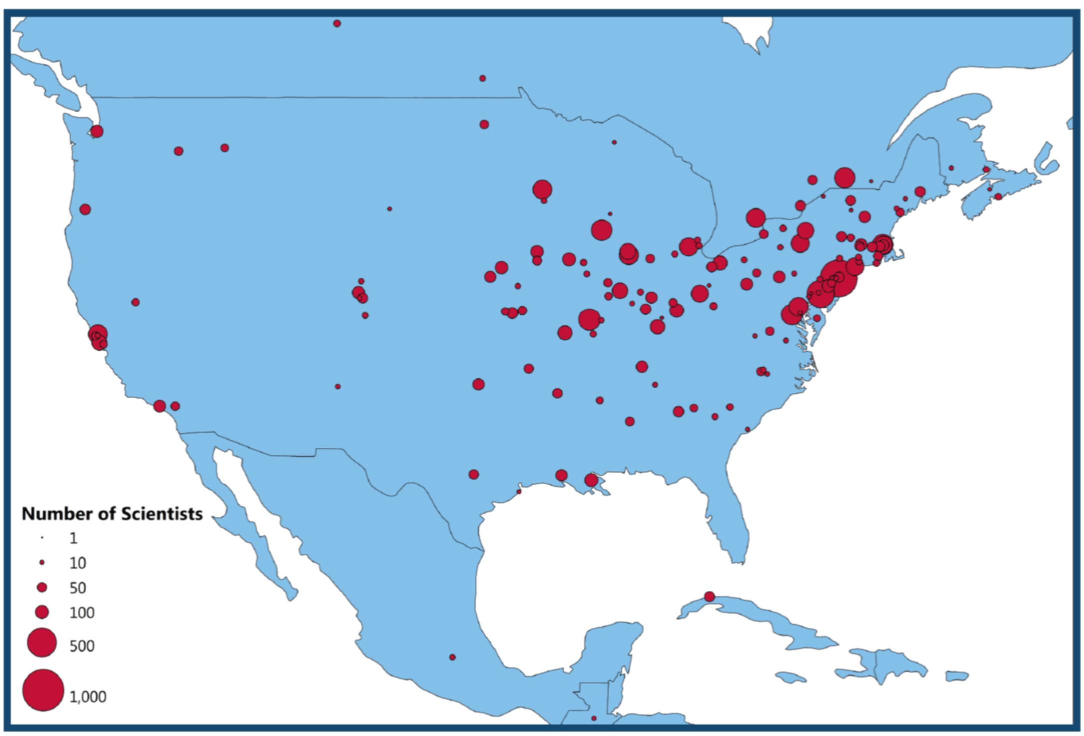


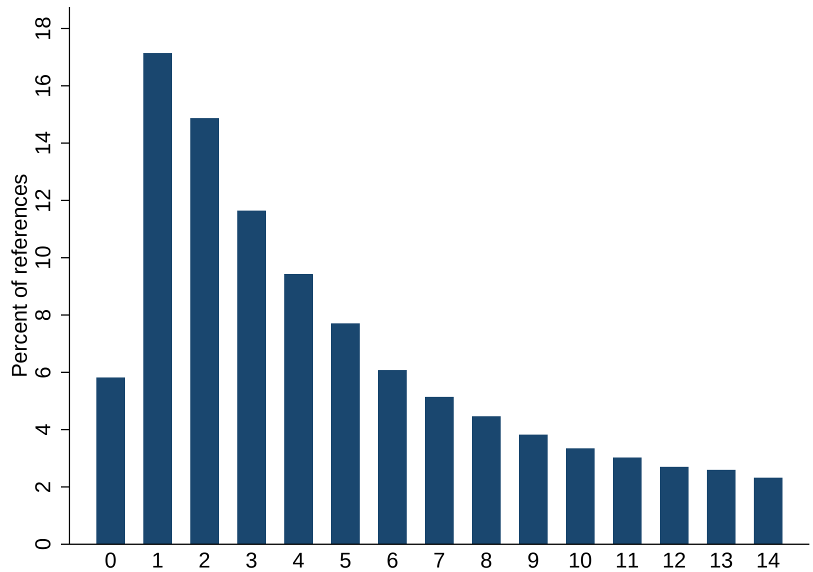
Figure A.4:
THE WORLD OF SCIENCE IN 1914





Notes: The map shows the total number of professors in all fields by city in 1914. Dot sizes are proportional to the number of professors. The scientist census data were collected by the authors from *Minerva - Handbuch der Gelehrten Welt* (see section 2 for details).

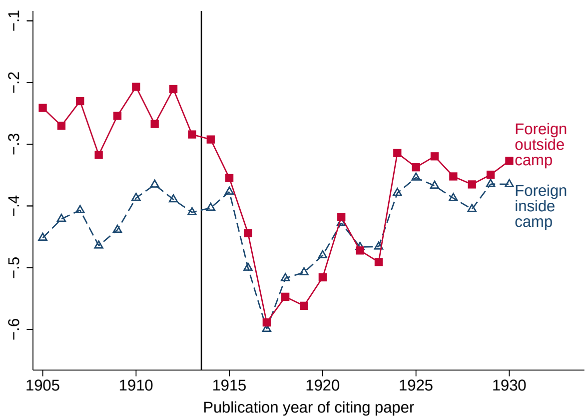
Figure A.5:
Distribution of Reference Age



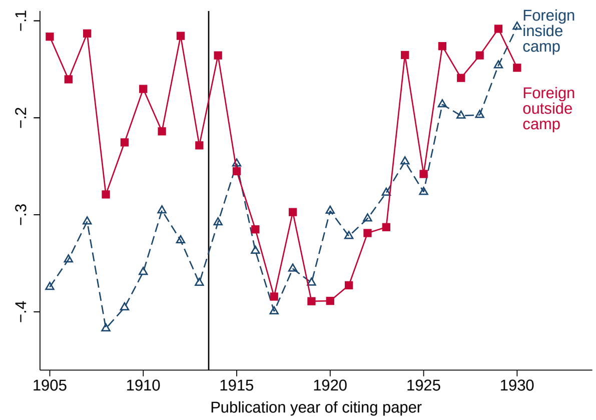
Notes: The Figure plots the percent of references that were published X years (X is plotted on the horizontal axis) before the citing paper. For example, 6% percent of references were published the same year as the citing paper and 17% of references were published one year before the citing paper. The distribution of reference age is computed for all citing papers published in our 160 top journals between 1905 and 1930. Only references that were published at most 14-years before the citing paper are considered for this calculation. The publication and citation data are from *ISI - Web of Science* (see section 2 for details).

Figure A.6:
International Citation Shares Relative to Home: Robustness Checks

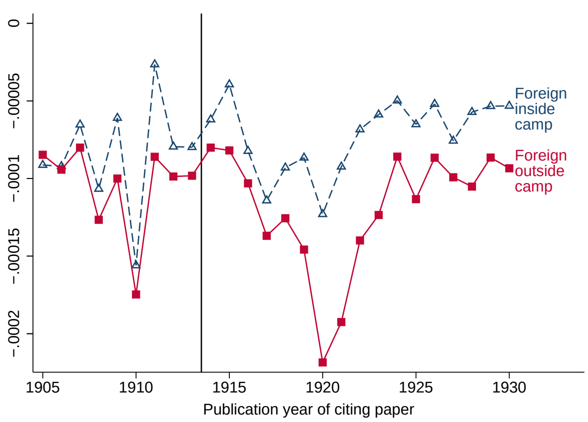
(a) Citing Scientists with University Position by 1914



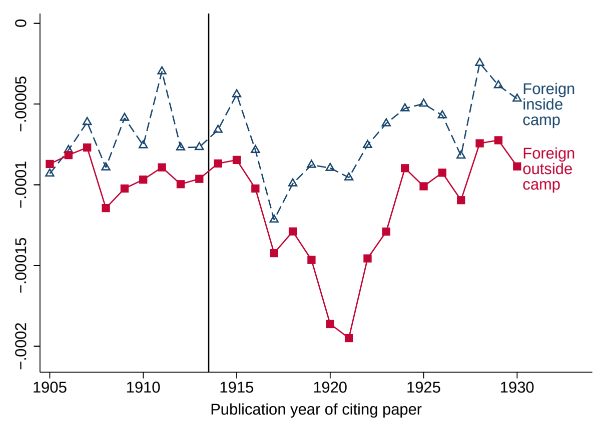
(b) Citing and Cited Scientists with University Position by 1914



(c) Citing and Cited Authors with University Position by 1914 and Normalize Shares



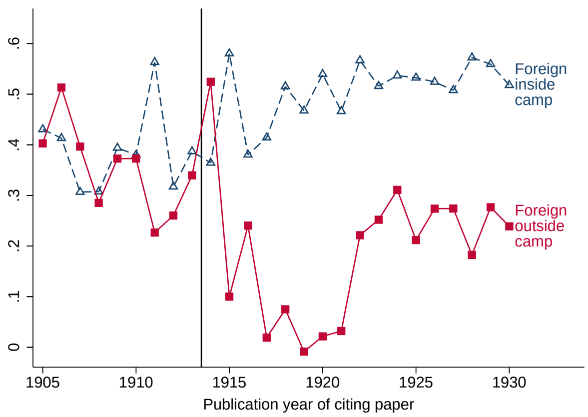
(d) Additionally Restrict Sample to Six Countries with Largest Scientific Output



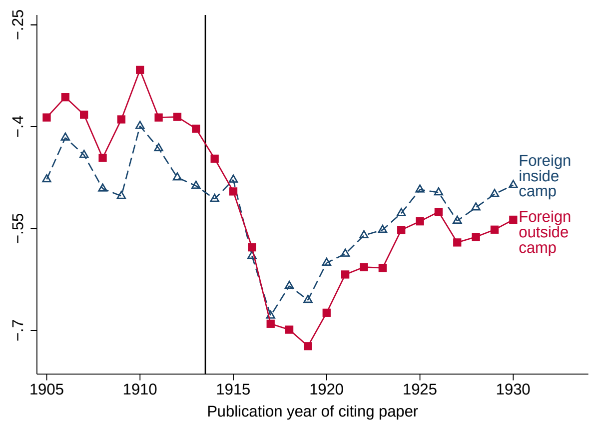
Notes: Panel (a) plots parameter estimates of regression (2) for citing authors with a university position by 1914. Panel (b) plots parameter estimates for citing scientists with a university position by 1914 and only considers citations to research published by scientists with a university position by 1914. In addition to the previous restrictions, panel (c) plots parameter estimates for a regression with normalized citation shares as the dependent variable. We normalize citation shares by the number of potentially citeable papers in each camp. Panel (d) plots parameter estimates where we further restrict the sample of citing and cited scientists to those from the six largest scientific countries in our data (USA, Germany, UK, Canada, Austria, and Hungary). In all panels, the "Foreign outside camp" line reports point estimates (ω_τ) that measure citation shares to research from outside the camp, relative to research from home. The "Foreign inside camp" line reports point estimates (ι_τ) that measure citation shares to research from foreign scientists inside the camp, relative to research from home. In all panels, we count citations to recent research, i.e. research published in the preceding five years. For example, the first dot (1905) measures relative citation shares to research published between 1901 and 1905, and so on. The data were collected by the authors and combine scientist census data from *Minerva - Handbuch der Gelehrten Welt* and publication and citation data from *ISI - Web of Science* (see section 2 for details).

Figure A.7:
International Citation Shares Relative to Home: Additional Robustness Checks

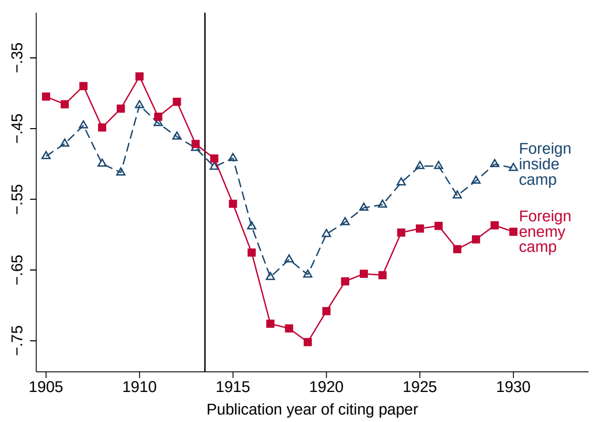
(a) Excluding U.S., German, and British Citing Papers



(b) Excluding Chemistry Citing Papers



(c) Relative Citation Shares to Enemy papers

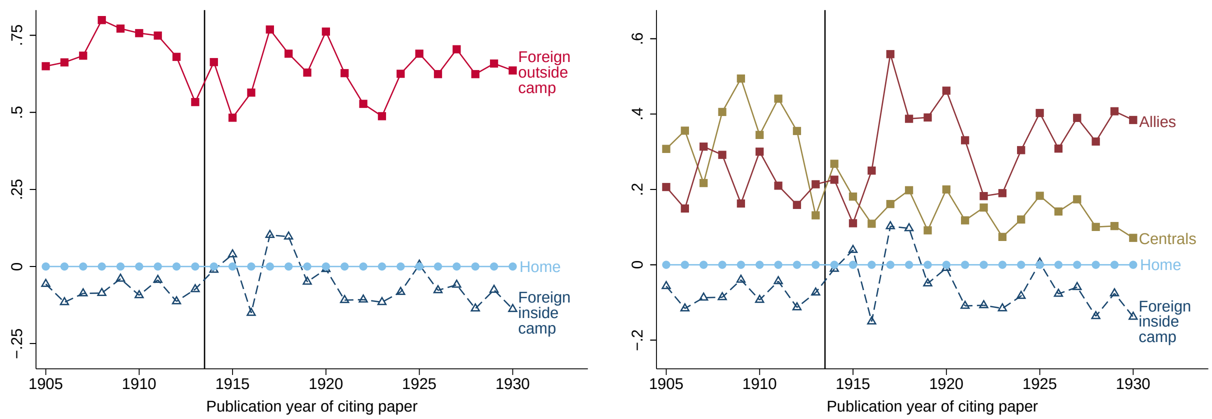


Notes: Panel (a) plots parameter estimates of regression (2), for a sample of papers published by scientists in smaller Allied or Central countries, i.e. scientists outside of the United States, Germany, and Britain. The "Foreign outside camp" line reports point estimates (ω_τ) that measure citation shares to research from outside the camp, relative to research from home. The "Foreign inside camp" line reports point estimates (ι_τ) that measure citation shares to research published by foreign scientists inside the camp, relative to research published at home. Panel (b) plots parameter estimates of regression (2), for a sample of papers that excludes papers published in chemistry journals. Panel (c) plots parameter estimates of a version of regression (2) in which the citation shares to research by scientists from outside the camp are further split into the share citing research from enemy countries and into the share citing research from other foreign countries (results not reported in the figure). In all panels, we focus on citations to recent research, i.e. research published in the preceding five years. For example, the first dot (1905) measures relative citation shares to research published between 1901 and 1905. The second dot (1906) measures relative citation shares to research published between 1902 and 1906, and so on. The data were collected by the authors and combine scientist census data from *Minerva - Handbuch der Gelehrten Welt* and publication and citation data from *ISI - Web of Science* (see section 2 for details).

Figure A.8:
International Citation Shares Relative to Home: Neutral Scientists

(a) Relative Reliance on Foreign Work

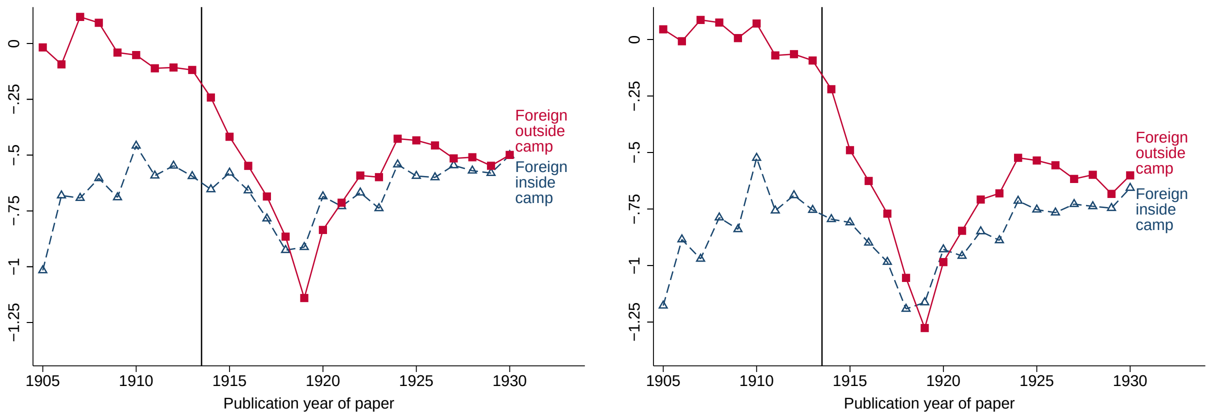
(b) Relative Reliance on Allied and Central Work



Notes: Each panel plots one set of parameter estimates of regression (2) for Neutral citing papers. In panel (a), the "Foreign outside camp" line reports point estimates (ω_τ) that measure citation shares to research from outside the Neutral camp, relative to research from home. The "Foreign inside camp" line reports point estimates (ι_τ) that measure citation shares to research from foreign scientists inside the Neutral camp, relative to research from home. In panel (b), the "Allies" line reports point estimates that measure citation shares to Allied research, relative to research from home. The "Centrals" line reports point estimates that measure citation shares to Central research, relative to research from home. The "Foreign inside camp" line reports point estimates that measure citation shares to research from foreign scientists inside the Neutral camp, relative to research from home. The regression also controls for citation shares to research by scientists from other countries. In both panels, we focus on citations to recent research, i.e. research published in the preceding five years. For example, the first dot (1905) measures relative citation shares to research published between 1901 and 1905, and so on. The data were collected by the authors and combine scientist census data from *Minerva - Handbuch der Gelehrten Welt* and publication and citation data from *ISI - Web of Science* (see section 2 for details).

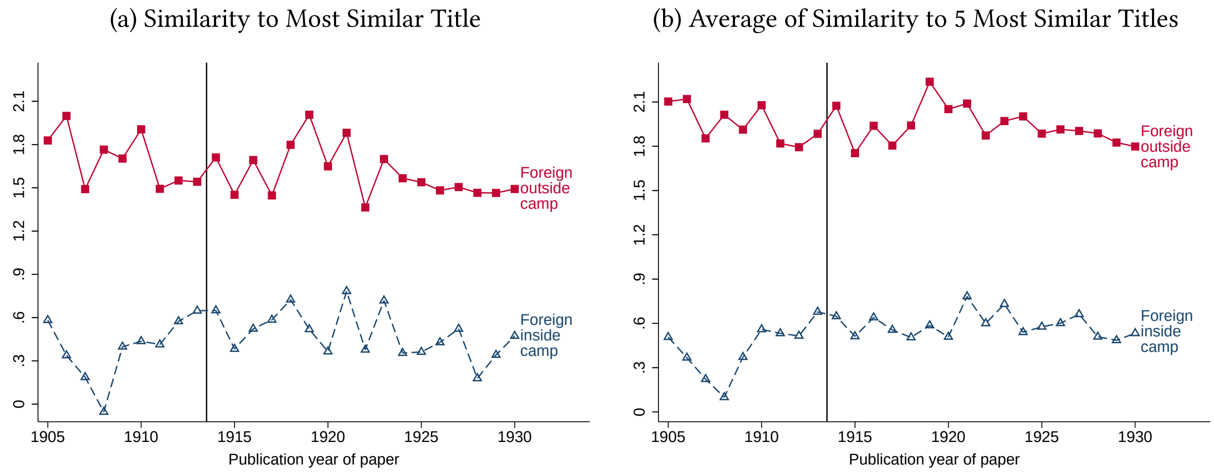
Figure A.9:
International Title Similarity Relative to Home: Excluding Chemistry Papers

(a) Similarity to Most Similar Title (b) Average Similarity to 5 Most Similar Titles



Notes: Each panel plots one set of parameter estimates of regression (2) where the dependent variable measures the standardized (i.e., mean 0 and standard deviation 1) LSA title similarity to papers by scientists from home, foreign countries inside the camp, and foreign countries outside the camp. In both panels, the sample of papers excludes papers published in chemistry journals. In panel (a), LSA title similarity is computed as the similarity to the most similar title from each camp. In panel (b), LSA title similarity is computed as the average similarity to the five most similar titles from each camp. The "Foreign outside camp" line reports point estimates (ω_τ) that measure the LSA title similarity to papers from outside the camp, relative to papers from home. The "Foreign inside camp" line reports point estimates (ι_τ) that measure the LSA title similarity to papers from foreign scientists inside the camp, relative to papers from home. We measure title similarity to recent papers, i.e. papers published in the preceding five years. For example, the first dot (1905) measures relative title similarity to papers published between 1901 and 1905. The data were collected by the authors and combine scientist census data from *Minerva - Handbuch der Gelehrten Welt* and publication and citation data from *ISI - Web of Science* (see section 2 for details).

Figure A.10:
International Title Similarity Relative to Home: Neutral Scientists

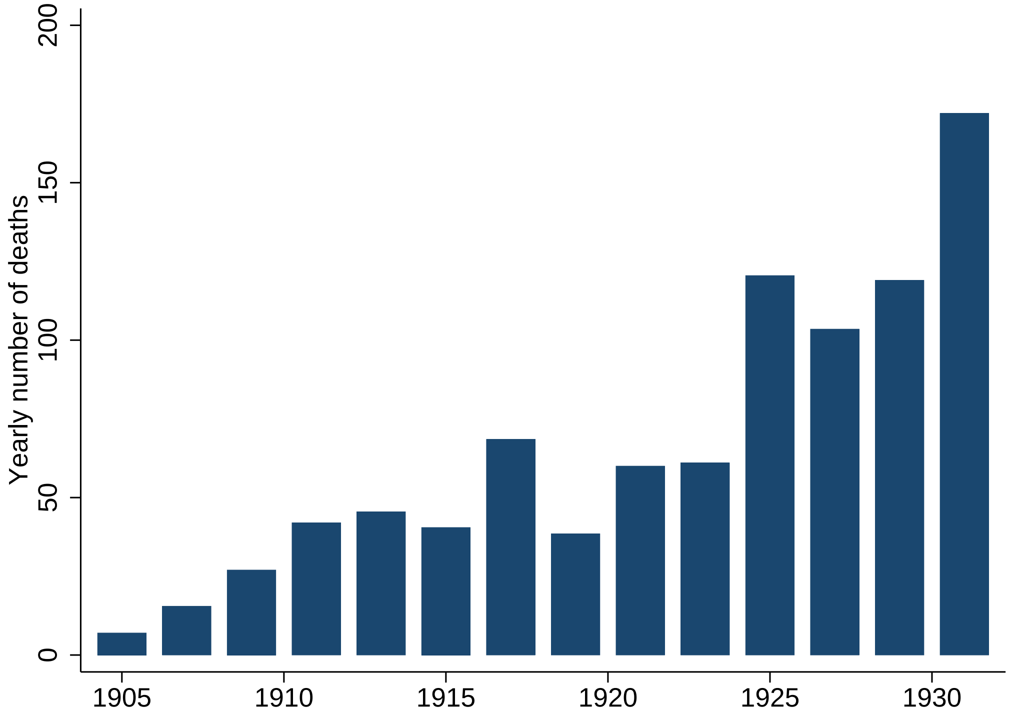


Notes: Each panel plots a set of parameter estimates of the equivalent of regression (2) for Neutral papers where the dependent variable measures the standardized (i.e., mean 0 and standard deviation 1) LSA title similarity. In panel (a), LSA title similarity is computed as the similarity to the most similar title from each camp. In panel (b), LSA title similarity is computed as the average similarity to the five most similar titles from each camp. The "Foreign outside camp" line reports point estimates (ω_τ) that measure the LSA title similarity to papers from outside the Neutral camp, relative to papers from home. The "Foreign inside camp" line reports point estimates (ι_τ) that measure the LSA title similarity to papers from foreign scientists inside the Neutral camp, relative to papers from home. In both panels, we focus on title similarity to recent papers, i.e. papers published in the preceding five years. For example, the first dot (1905) measures relative title similarity to research published between 1901 and 1905. The data were collected by the authors and combine scientist census data from *Minerva - Handbuch der Gelehrten Welt* and publication and citation data from *ISI - Web of Science* (see section 2 for details).

Figure A.11:
Average Productivity of Scientists

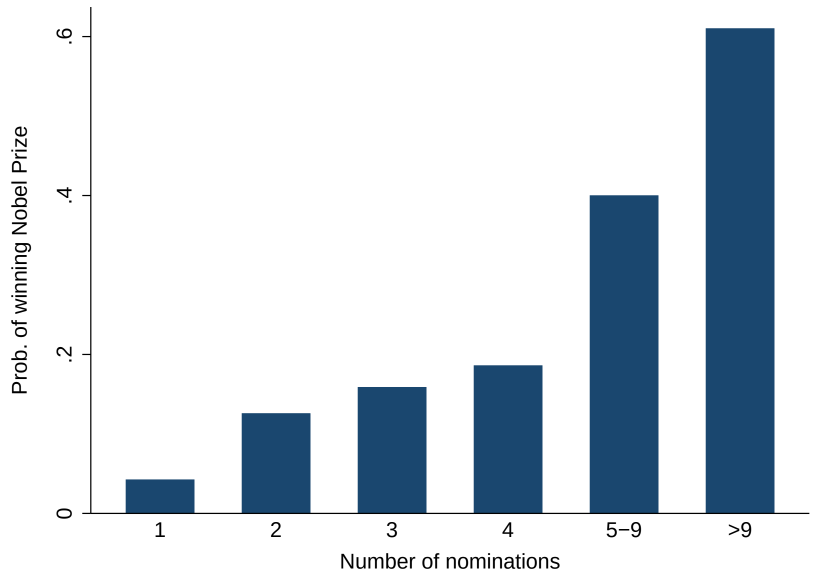
Notes: The Figure plots the average number of publications for the sample of 8,734 scientists used to estimate regression (3). The yearly number of publications of each scientist is measured by the number of publications in any of the top 160 journals in our data. The data were collected by the authors and combine scientist census data from *Minerva - Handbuch der Gelehrten Welt* and publication and citation data from *ISI - Web of Science* (see section 2 for details).

Figure A.12:
Death Years of Scientists in Productivity Sample



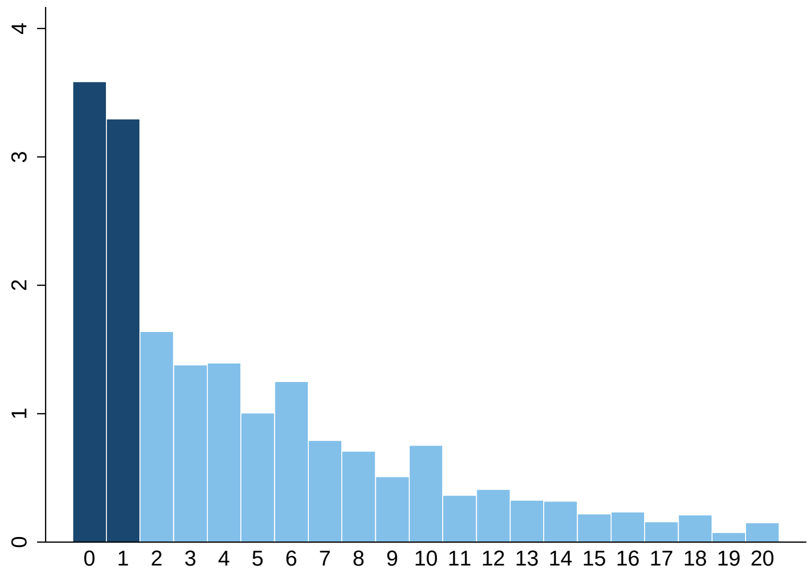
Notes: The Figure plots yearly deaths in two-year bins for scientists in the productivity sample. The data on deaths were collected by the authors from obituaries in *Science*, *Nature*, *Kürschners Deutscher Gelehrtenkalender*, *Sitzungsberichte der Preussischen Akademie*, and *Physikalische Zeitschrift* (see Appendix E.6 for details).

Figure A.13:
Probability of Winning Nobel Prize Depending on Number of Nominations



Notes: The Figure plots the probability of winning the Nobel Prize depending on the number of nominations. The number of nominations is the sum of nominations in year t and year $t-1$ if year t is a candidate's last nomination in the interval 1905 to 1945. The data were collected by the authors from Nobelprize.org (2014) and include 991 candidates for the Nobel Prize and 131 winners. The data contain 589 candidates with one nomination, 159 with two nominations, 63 with three nominations, 43 with four nominations, 80 with five to nine nominations, and 59 with more than nine nominations.

Figure A.14:
Nominations per Year for Eventual Nobel Prize Winners



Notes: The Figure plots the average number of nominations per year for eventual Nobel Prize winners, relative to the year of the award. For example, the first bar from the left (0) shows that Nobel Laureates on average receive 3.6 nominations in the winning year. Similary, the second bar from the left (1) shows that Nobel Laureates receive on average 3.3 nominations the year before the winning year. The data were collected by the authors from Nobelprize.org (2014) and include 131 Nobel Prize winners.

A.2 Appendix Tables

Table A.1:
SUMMARY STATISTICS: SCIENTISTS

	Minerva 1900	*Minerva 1914*
Panel (a): Scholars from all fields		
Number of universities	569	973
Total number of university scholars	24,166	42,226
Scholars with name information	23,917	36,777
Panel (b): Scientists from all fields		
Total scientists (5 fields)	10,133	15,891
Medicine	5,413	8,829
Biology	1,486	2,353
Chemistry	1,317	2,077
Physics	1,167	1,626
Mathematics	1,062	1,440

Notes: Panel (a) reports the number of university professors in all fields. Panel (b) focuses on university professors in the five scientific fields used throughout the paper. The entry of "Total scientists (5 fields)" is smaller than the sum of the 5 fields below because some scientists work in multiple fields. The data were collected by the authors from two volumes (1900 and 1914) of *Minerva - Handbuch der Gelehrten Welt* (see section 2 for details).

Table A.2:
Solvay Conferences in Physics: Allies and Centrals

	1911	*1913*	*1921*	*1924*	*1927*	*1930*
ALLIES	M. Brillouin (FR)	W. Barlow (UK)	C. Barkla (UK, '17)	E. Bauer (FR)	W. Bragg (UK, '15)	E. Bauer (FR)
	M. Curie (FR, '03, '11)	W. Bragg (UK, '15)	W. Bragg (UK, '15)	W. Bragg (UK, '15)	L. Brillouin (FR)	L. Brillouin (FR)
	M. de Broglie (FR)	M. Brillouin (FR)	L. Brillouin (FR)	P. Bridgman (USA, '46)	L. de Broglie (FR, '29)	A. Cotton (FR)
	R. Goldschmidt (BE)	M. Curie (FR, '03, '11)	M. Brillouin (FR)	L. Brillouin (FR)	A. Compton (USA, '27)	M. Curie (FR, '03, '11)
	É. Herzen (BE)	M. de Broglie (FR)	M. Curie (FR, '03, '11)	M. Brillouin (FR)	M. Curie (FR, '03, '11)	C. Darwin (UK)
	G. Hostelet (BE)	R. Goldschmidt (BE)	M. de Broglie (FR)	W. Broniewski (PL)	T. de Donder (BE)	T. de Donder (BE)
	J. Jeans (UK)	L. Gouy (FR)	É. Herzen (BE)	M. Curie (FR, '03, '11)	P. Dirac (UK, '33)	P. Dirac (UK, '33)
	P. Langevin (FR)	É. Herzen (BE)	P. Langevin (FR)	T. de Donder (BE)	R. Fowler (UK)	J. Errera (BE)
	J. Perrin (FR, '26)	G. Hostelet (BE)	J. Larmor (UK)	E. Hall (USA)	É. Henriot (BE)	E. Fermi (ITA, '38)
	H. Poincaré (FR)	J. Jeans (UK)	A. Michelson (USA, '07)	É. Henriot (BE)	É. Herzen (BE)	É. Henriot (BE)
	E. Rutherford (UK, '08)	P. Langevin (FR)	R. Millikan (USA, '23)	É. Herzen (BE)	P. Langevin (FR)	É. Herzen (BE)
	E. Solvay (BE)	W. Pope (UK)	J. Perrin (FR, '26)	P. Langevin (FR)	I. Langmuir (USA, '32)	P. Kapitza (UK)
		E. Rutherford (UK, '08)	O. Richardson (UK, '28)	F. Lindemann (UK)	A. Piccard (BE)	P. Langevin (FR)
		J. J. Thomson (UK, '06)	E. Rutherford (UK, '08)	A. Piccard (BE)	O. Richardson (UK, '28)	C. Manneback (BE)
		R. Wood (USA)	E. Solvay (BE)	O. Richardson (UK, '28)	E. van Aubel (BE)	A. Piccard (BE)
			E. van Aubel (BE)	W. Rosenhain (UK)	J. Verschaffelt (BE)	O. Richardson (UK, '28)
			P. Weiss (FR)	E. Rutherford (UK, '08)	C. Wilson (UK, '27)	J. Van Vleck (USA, '77)
				E. van Aubel (BE)		J. Verschaffelt (BE)
				J. Verschaffelt (BE)		P. Weiss (FR)
CENTRALS	A. Einstein (AU, '21)	E. Grüneisen (GE)			M. Born (GE, '54)	P. Debye (GE, '36)
	F. Hasenöhrl (AU)	F. Hasenöhrl (AU)			P. Debye (GE, '36)	A. Einstein (GE, '21)
	F. Lindemann (GE)	F. Lindemann (GE)			A. Einstein (GE, '21)	W. Gerlach (GE)
	W. Nernst (GE, '20)	W. Nernst (GE, '20)			W. Pauli (GE, '45)	W. Heisenberg (GE, '32)
	M. Planck (GE, '18)	H. Rubens (GE)			M. Planck (GE, '18)	A. Sommerfeld (GE)
	H. Rubens (GE)	A. Sommerfeld (GE)				O. Stern (GE, '43)
	A. Sommerfeld (GE)	W. Voigt (GE)				
	E. Warburg (GE)	E. Warburg (GE)				
	W. Wien (GE, '11)	W. Wien (GE, '11)				

Table A.2:
SOLVAY CONFERENCES IN PHYSICS: NEUTRALS AND REST

	1911	*1913*	*1921*	*1924*	*1927*	*1930*
NEUTRALS	M. Knudsen (DK)	A. Einstein (SWZ, '21)	W. de Haas (NE)	P. Debye (SWZ, '36)	N. Bohr (DK, '22)	N. Bohr (DK, '22)
	H. Lorentz (NE, '02)	H. Lorentz (NE, '02)	P. Ehrenfest (NE)	G. de Hevesy (DK, '43)	P. Ehrenfest (NE)	B. Cabrera (SPA)
	H. Onnes (NE, '13)	M. Knudsen (DK)	M. Knudsen (DK)	W. Keesom (NE)	C. Guye (SWZ)	W. de Haas (NE)
		H. Onnes (NE, '13)	H. Lorentz (NE, '02)	M. Knudsen (DK)	W. Heisenberg (DK, '32)★	B. Felipe (SPA)
		J. Verschaffelt (NE)	H. Onnes (NE, '13)	H. Lorentz (NE, '02)	M. Knudsen (DK)	C. Guye (SWZ)
		M. von Laue (SWZ, '14)	K. Siegbahn (SWE, '24)	H. Onnes (NE, '13)	H. Kramers (NE)	M. Knudsen (DK)
		P. Weiss (SWZ)	J. Verschaffelt (NE)	E. Schrödinger (SWZ, '33)	H. Lorentz (NE, '02)	H. Kramers (NE)
			P. Zeeman (NE, '02)		E. Schrödinger (SWZ, '33)★	W. Pauli (SWZ, '45)
						P. Zeeman (NE, '02)
REST				A. Joffé (RUS)		J. Dorfman (RUS)
						P. Kapitsa (RUS, '78)

Notes: The Table reports delegates at each *Solvay Conference* in Physics between 1911 and 1930. In brackets, after the name, we report the country of residence at the moment of the conference and the year when a delegate won a Nobel prize. The data were collected by the authors from Mehra (1975) (see Appendix E.3 for details).
★ Even though classified as Neutrals in Mehra's data, Heisenberg and Schrödinger were de facto in the German system in 1927. Heisenberg had a joint appointment at the German University of Göttingen and the Danish University of Copenhagen and moved to a permanent position at the German University of Leipzig in 1927. Schrödinger moved to the German University of Berlin in 1927.

Table A.3:
LIST OF SCIENTIFIC JOURNALS

Country	Field	Journal title
USA	General	American Journal of Science
USA	General	Proceedings of the National Academy of Sciences of the United States of America
USA	General	Proceedings of the American Academy of Arts and Sciences
USA	General	Review of Scientific Instruments
USA	General	Science
USA	Medicine	American Journal of Physiology
USA	Medicine	Archives of Pathology and Laboratory Medicine
USA	Medicine	Archives of Pathology
USA	Medicine	Contributions to Embryology
USA	Medicine	Journal of Experimental Medicine
USA	Medicine	Journal of Infectious Diseases
USA	Medicine	Journal of Urology
USA	Medicine	Journal of the American Medical Association
USA	Medicine	Medicine
USA	Medicine	New England Journal of Medicine
USA	Bio./Med.	Anatomical Record
USA	Bio./Med.	Endocrinology
USA	Bio./Med.	Genetics
USA	Bio./Med.	Journal of Clinical Endocrinology
USA	Bio./Med.	Journal of General Physiology
USA	Bio./Med.	Journal of Immunology
USA	Bio./Med.	Journal of Morphology
USA	Bio./Med.	Journal of Morphology and Physiology
USA	Bio./Med.	Physiological Reviews
USA	Bio./Med.	Proceedings of the Society for Experimental Biology and Medicine
USA	Biology	American Journal of Anatomy
USA	Biology	American Journal of Botany
USA	Biology	American Journal of Pathology
USA	Biology	American Naturalist
USA	Biology	Biological Bulletin
USA	Biology	Botanical Gazette
USA	Biology	Ecology
USA	Biology	Journal of Bacteriology
USA	Biology	Journal of Economic Entomology
USA	Biology	Journal of Experimental Zoology
USA	Biology	Journal of Medical Research
USA	Biology	Journal of Heredity
USA	Biology	Phytopathology
USA	Biology	Plant Physiology
USA	Biology	Quarterly Review of Biology

Table A.3:
List of Scientific Journals

Country	Field	Journal title
USA	Pharmac.	Journal of Pharmacology and Experimental Therapeutics
USA	Biochem.	Journal of Biological Chemistry
USA	Biochem.	Stain Technology
USA	Chemistry	Chemical Reviews
USA	Chemistry	Industrial and Engineering Chemistry
USA	Chemistry	Industrial and Engineering Chemistry, Analytical Edition
USA	Chemistry	Journal of the American Chemical Society
USA	Chemistry	Organic Syntheses
USA	Chemistry	Transactions of the American Institute of Chemical Engineers
USA	Phys. Chem.	Journal of Physical Chemistry
USA	Physics	Journal of the Optical Society of America
USA	Physics	Journal of the Optical Society of America and review of scientific instruments
USA	Physics	Physical Review
USA	Physics	Review of Modern Physics
USA	Math. Phys.	Proceedings of the IRE
USA	Mathematics	American Journal of Mathematics
USA	Mathematics	Annals of Mathematical Statistics
USA	Mathematics	Annals of Mathematics
USA	Mathematics	Journal of the American Statistical Association
USA	Mathematics	Journal of the Franklin Institute
USA	Mathematics	Publications of the American Statistical Association
USA	Mathematics	Quarterly Publications of the American Statistical Association
USA	Mathematics	Transactions of the American Mathematical Society
UK	General	Nature
UK	General	Philosophical Magazine
UK	General	Proceedings of the Cambridge Philosophical Society
UK	General	Proceedings of the Royal Society of London
UK	Medicine	Journal of Anatomy
UK	Medicine	Journal of Pathology and Bacteriology
UK	Medicine	Lancet
UK	Medicine	Quarterly Journal of Medicine
UK	Bio./Med.	British Journal of Experimental Pathology
UK	Bio./Med.	Quarterly Journal of Experimental Physiology and Cognate Medical Sciences
UK	Bio./Med.	Quarterly Journal of Experimental Physiology
UK	Biology	Annals of Applied Biology
UK	Biology	Annals of Botany
UK	Biology	Annals of Eugenics
UK	Biology	Biological Reviews of the Cambridge Philosophical Society
UK	Biology	Biological Reviews and Biological Proceedings of the Cambridge Philos. Soc.
UK	Biology	British Journal of Experimental Biology
UK	Biology	Journal of Ecology

Table A.3:
List of Scientific Journals

Country	Field	Journal title
UK	Biology	Journal of Experimental Biology
UK	Biology	Journal of Genetics
UK	Biology	Philos. Trans. of the Royal Soc. of Lond. Ser. B, Cont. Papers of a Biolog. Charac.
UK	Biology	Philosoph. Transact. of the Royal Soc. of London Ser. B-Biol. Sciences
UK	Biology	Proceedings of the Zoological Society of London
UK	Biology	Proceedings of the Cambridge Philosophical Society-Biological Sciences
UK	Biology	Proceedings of the Royal Soc. of London Series B, Cont. Papers of a Biol. Charac.
UK	Biology	Proce. of the Zoological Society of London Series A-General and Experimental
UK	Biology	Proce. of the Zoolog. Soc. of London Series B-Systematic and Morphological
UK	Biology	Quarterly Journal of Microscopical Science
UK	Biochem.	Biochemical Journal
UK	Chemistry	Journal of the Chemical Society
UK	Chemistry	Transactions of the Faraday Society
UK	Physics	Astrophysical Journal
UK	Physics	Monthly Notices of the Royal Astronomical Society
UK	Physics	Proceedings of the Physical Society Of London
UK	Physics	Proceedings of the Physical Society
UK	Math. Phys.	Phil. Trans. of the Roy. Soc. of Lond. Ser. A, Cont. Pap. of a Math. or Phys. Char.
UK	Math. Phys.	Philos. Trans. of the Royal Society of London Series A-Math. and Phys. Sciences
UK	Math. Phys.	Proce. of the Roy. Soc. of Lon. Ser. A, Cont. Papers of a Math. and Phys. Char.
UK	Math. Phys.	Proce. of the Roy. Soc. of Lon. Ser. A-Math. and Phys. Sciences
UK	Mathematics	Biometrika
UK	Mathematics	Journal of the Royal Statistical Society
UK	Mathematics	Proceedings of the London Mathematical Society
Germany	General	Archiv für Experimentelle Pathologie und Pharmakologie
Germany	General	Hoppe-Seylers Zeitschrift fur Physiologische Chemie
Germany	General	Naturwissenschaften
Germany	General	Naunyn-Schmied. Archiv für Experiment. Pathologie und Pharmakologie
Germany	General	Sitzungsberichte der Königlich Preussischen Akademie der Wissenschaften
Germany	Medicine	Archiv für Patholog. Anatomie und Physiol. und für Klinische Medicin
Germany	Medicine	Journal für Psychologie und Neurologie
Germany	Medicine	Virch. Archiv für Patholog. Anato. und Physiol. und für Klinis. Medizin
Germany	Medicine	Zeitschrift für die Gesamte Neurologie und Psychiatrie
Germany	Bio./Med.	Archiv für Mikroskopische Anatomie
Germany	Bio./Med.	Archiv für Mikroskopische Anatomie und Entwicklungsgeschichte
Germany	Bio./Med.	Archiv für die Gesamte Physiologie des Menschen und der Tiere
Germany	Bio./Med.	Archiv für Mikroskopische Anatomie und Entwicklungsmechanik
Germany	Bio./Med.	Beitrage zur Pathologischen Anatomie und zur Allgemeinen Pathologie
Germany	Bio./Med.	Pflugers Archiv für die Gesamte Physiologie des Menschen und der Tiere
Germany	Bio./Med.	Wilhelm Roux' Archiv für Entwicklungsmechanik der Organismen

Table A.3:
LIST OF SCIENTIFIC JOURNALS

Country	Field	Journal title
Germany	Biology	Archiv für Entwicklungsmechanik der Organismen
Germany	Biology	Archiv für Experimentelle Zellforschung
Germany	Biology	Zeitschrift für Biologie
Germany	Biology	Zeitschrift für Wissenschaftliche Zoologie
Germany	Biochem.	Biochemische Zeitschrift
Germany	Chemistry	Berichte der Deutschen Chemischen Gesellschaft
Germany	Chemistry	Journal für Praktische Chemie-Leipzig
Germany	Chemistry	Justus Liebigs Annalen der Chemie
Germany	Chemistry	Kolloid Zeitschrift
Germany	Chemistry	Zeitschrift für Anorganische und Allgemeine Chemie
Germany	Chemistry	Zeitschrift für Elektrochemie
Germany	Chemistry	Zeitschrift für Elektrochemie und Angewandte Physikalische Chemie
Germany	Chemistry	Zeitschrift für Kristallographie
Germany	Chemistry	Zeitschrift für Krystallographie und Mineralogie
Germany	Chemistry	Zeitschrift für Anorganische Chemie
Germany	Phys. Chem.	Zeitschrift für Physikalische Chemie Stochiometrie und Verwandtschaftslehre
Germany	Phys. Chem.	Zeitsch. für Physik. Chem.-Abteil. A-Chem. Therm. Kinet. Elektroche. Eigens.
Germany	Phys. Chem.	Zeitsch. für Physik. Chem.-Abteil. B-Chem. der Elementarproz. Aufb. der Mater.
Germany	Physics	Annalen der Physik
Germany	Physics	Physikalische Zeitschrift
Germany	Physics	Zeitschrift für Physik
Germany	Math. Phys.	Sitzungsbe. der Preussi. Akad. der Wissensch. Physik.-Mathem. Klasse
Germany	Mathematics	Journal für die Reine und Angewandte Mathematik
Germany	Mathematics	Mathematische Annalen
Germany	Mathematics	Mathematische Zeitschrift
Germany	Mathematics	Zeitschrift für Angewandte Mathematik und Mechanik
France	General	Comptes Rendus Hebdomadaires des Seances de L'Academie des Sciences
France	Biology	Comptes Rendus des Seances de la Societe de Biologie et de ses Filiales
France	Chemistry	Annales de Chimie France
France	Phys. Chem.	Annales de Chemie et de Physique
France	Physics	Journal de Physique et le Radium
Netherlands	General	Proceedings of the Koninklijke Nederlandse Akademie van Wetenschappen
Netherlands	General	Proce. of the Koninkl. Nederlan. Akad. van Wetenschap. te Amsterdam
Netherlands	Chemistry	Recueil des Travaux Chimiques des Pays-Bas
Netherlands	Chemistry	Recueil des Travaux Chimiques des Pays-Bas et de la Belgique
Sweden	Bio./Med.	Hereditas
Sweden	Bio./Med.	Skandinavisches Archiv fur Physiologie
Sweden	Mathematics	Acta Mathematica
Switzerland	Chemistry	Helvetica Chimica Acta

Notes: The Table reports the 160 journals used in the analysis ordered by country and field. Journal data were collected by the authors from *ISI - Web of Science* (see section 2 for details).

Table A.4:
SUMMARY STATISTICS: PUBLICATIONS BY JOURNAL COUNTRY

	(1)	(2)	(3)	(4)	(5)
	Share publications in journal country				
	U.S.A.	*U.K.*	*France*	*Germany*	*Others*
Allies:					
U.S.A.	**0.93**	0.04	0.00	0.03	0.00
U.K.	0.11	**0.83**	0.00	0.05	0.00
Canada	**0.71**	0.25	0.00	0.04	0.00
Japan	0.31	0.17	0.00	**0.51**	0.01
France	0.20	0.14	**0.38**	0.26	0.02
Italy	0.10	0.10	0.00	**0.79**	0.00
Australia	0.38	**0.57**	0.00	0.05	0.00
Poland	0.20	0.27	0.00	**0.48**	0.05
Ireland	0.34	**0.59**	0.00	0.07	0.00
Belgium	0.14	0.06	**0.64**	0.14	0.02
New Zealand	0.23	**0.73**	0.00	0.03	0.00
Romania	0.11	0.00	0.21	**0.68**	0.00
Brazil	0.00	0.11	0.00	**0.89**	0.00
South Africa	0.14	**0.71**	0.00	0.14	0.00
Greece	0.00	0.00	0.00	**1.00**	0.00
Portugal	**1.00**	0.00	0.00	0.00	0.00
Centrals:					
Germany	0.01	0.01	0.00	**0.98**	0.00
Austria	0.03	0.01	0.00	**0.95**	0.01
Hungary	0.05	0.01	0.00	**0.92**	0.01

Notes: The Table reports where scientists from each country published their papers. The data were collected by the authors and combine scientist census data from *Minerva - Handbuch der Gelehrten Welt* and publication and citation data from *ISI - Web of Science* (see section 2 for details).

Table A.5:
INTERNATIONAL CITATION SHARES RELATIVE TO HOME

	Par. Est.	*Std. Er.*		*Par. Est.*	*Std. Er.*
Foreign outside × 1905	-0.323	0.073	Foreign inside × 1905	-0.489	0.060
Foreign outside × 1906	-0.340	0.069	Foreign inside × 1906	-0.471	0.074
Foreign outside × 1907	-0.325	0.078	Foreign inside × 1907	-0.446	0.066
Foreign outside × 1908	-0.383	0.067	Foreign inside × 1908	-0.500	0.060
Foreign outside × 1909	-0.359	0.070	Foreign inside × 1909	-0.512	0.053
Foreign outside × 1910	-0.301	0.075	Foreign inside × 1910	-0.417	0.065
Foreign outside × 1911	-0.381	0.075	Foreign inside × 1911	-0.442	0.057
Foreign outside × 1912	-0.350	0.090	Foreign inside × 1912	-0.461	0.064
Foreign outside × 1913	-0.397	0.075	Foreign inside × 1913	-0.477	0.055
Foreign outside × 1914	-0.432	0.094	Foreign inside × 1914	-0.504	0.078
Foreign outside × 1915	-0.493	0.067	Foreign inside × 1915	-0.492	0.079
Foreign outside × 1916	-0.570	0.071	Foreign inside × 1916	-0.588	0.067
Foreign outside × 1917	-0.676	0.059	Foreign inside × 1917	-0.660	0.061
Foreign outside × 1918	-0.696	0.057	Foreign inside × 1918	-0.635	0.056
Foreign outside × 1919	-0.715	0.064	Foreign inside × 1919	-0.657	0.065
Foreign outside × 1920	-0.664	0.069	Foreign inside × 1920	-0.599	0.079
Foreign outside × 1921	-0.616	0.079	Foreign inside × 1921	-0.582	0.078
Foreign outside × 1922	-0.609	0.073	Foreign inside × 1922	-0.562	0.070
Foreign outside × 1923	-0.615	0.062	Foreign inside × 1923	-0.558	0.058
Foreign outside × 1924	-0.540	0.076	Foreign inside × 1924	-0.526	0.065
Foreign outside × 1925	-0.542	0.074	Foreign inside × 1925	-0.503	0.069
Foreign outside × 1926	-0.531	0.073	Foreign inside × 1926	-0.503	0.066
Foreign outside × 1927	-0.571	0.070	Foreign inside × 1927	-0.545	0.064
Foreign outside × 1928	-0.551	0.066	Foreign inside × 1928	-0.524	0.058
Foreign outside × 1929	-0.533	0.070	Foreign inside × 1929	-0.500	0.066
Foreign outside × 1930	-0.550	0.064	Foreign inside × 1930	-0.506	0.063
Paper FE			YES		
Observations			105,378		
Number of papers			35,126		

Notes: The table reports parameter estimates of regression (2). "Foreign outside" measures citation shares to research from outside the camp, relative to research from home. "Foreign inside" measures citation shares to research from foreign scientists inside the camp, relative to research from home. We count citations to recent research, i.e. research published in the preceding five years. For example, "Foreign outside × 1905" measures relative citation shares to research from outside the camp published between 1901 and 1905. Similarly, "Foreign outside in 1906" measures relative citation shares to research from outside the camp published between 1902 and 1906. Standard errors are clustered at the country-times-field level. The data were collected by the authors and combine scientist census data from *Minerva - Handbuch der Gelehrten Welt* and publication and citation data from *ISI - Web of Science* (see section 2 for details).

Table A.6:
CHANGES IN INTERNATIONAL CITATIONS: BY CAMP

Dependent variable: *Citation Shares to recent research*	(1)	(2) AL citing papers	(3) CE citing papers
Foreign *outside* camp × WWI	-0.229***	-0.180***	0.047
	(0.034)	(0.030)	(0.037)
Foreign *outside* camp × Boycott	-0.258***	-0.211***	-0.192***
	(0.052)	(0.040)	(0.062)
Foreign *outside* camp × Post Boycott	-0.213***	-0.175***	-0.085
	(0.051)	(0.040)	(0.104)
Foreign *inside* camp × WWI	-0.148***	-0.156***	-0.011
	(0.045)	(0.039)	(0.037)
Foreign *inside* camp × Boycott	-0.164***	-0.153**	-0.160**
	(0.057)	(0.059)	(0.072)
Foreign *inside* camp × Post Boycott	-0.154**	-0.132**	-0.172
	(0.059)	(0.063)	(0.120)
Paper FE	YES	YES	YES
Camp FE	YES	YES	YES
Foreign *in/outside* time trends	YES	YES	YES
Observations	105,378	87,060	18,318
Number of citing papers	35,126	29,020	6,106
Within R-squared	0.335	0.429	0.186

Notes: Each column reports one set of parameter estimates of regression (1) for citing papers published between 1905 and 1930. Column (1) reports results for all Allied and Central citing papers in our sample. Column (2) reports results for Allied citing papers, only, and column (3) reports results for Central citing papers, only. In all columns, the dependent variable measures the share of references to research by scientists from home, foreign countries inside the camp, and foreign countries outside the camp. We count citations to recent research, i.e. research published in the preceding five years, e.g. 1901-1905 for citing papers published in 1905, 1902-1906 for citing papers published in 1906, and so on. The reference/omitted category is the citation share to research from home. Standard errors are clustered at the country-times-field level. Significance levels: *** p<0.01, ** p<0.05, and * p<0.1. The data were collected by the authors and combine scientist census data from *Minerva - Handbuch der Gelehrten Welt* and publication and citation data from *ISI - Web of Science* (see section 2 for details).

Table A.7:
Changes in International Citations: Including Self-Citations in Home

Dependent variable:	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Cit. Sh. to recent research	*All papers*		Frontier: 5%		Frontier: 3%		Frontier: 1%	
Foreign *outside* camp × Post 1914	-0.204***	-0.232***	-0.049***	-0.090***	-0.032***	-0.063***	-0.019***	-0.038***
	(0.032)	(0.035)	(0.015)	(0.019)	(0.012)	(0.012)	(0.005)	(0.006)
Foreign *inside* camp × Post 1914	-0.078**	-0.137***	-0.023*	-0.066***	-0.018*	-0.048***	-0.012**	-0.033***
	(0.038)	(0.044)	(0.013)	(0.020)	(0.010)	(0.012)	(0.005)	(0.006)
Paper FE	YES	YES	YES	YES	YES	YES	YES	YES
Camp FE	YES	YES	YES	YES	YES	YES	YES	YES
Non-frontier research interactions			YES	YES	YES	YES	YES	YES
Foreign *in/outside* time trends		YES		YES		YES		YES
Observations	116,229	116,229	232,458	232,458	232,458	232,458	232,458	232,458
Number of citing papers	38,743	38,743	38,743	38,743	38,743	38,743	38,743	38,743
Within R-squared	0.416	0.417	0.290	0.290	0.360	0.360	0.464	0.464

Notes: Each column reports one set of parameter estimates of regression (1) for citing papers published between 1905 and 1930. In columns (1)-(2) the dependent variable measures citation shares to research by scientists from home *inclusive* of self-citations, foreign countries inside the camp, and foreign countries outside the camp. In columns (3) to (8) the dependent variable measures citation shares to frontier and non-frontier research by scientists from home *inclusive* of self-citations, foreign countries inside the camp, and foreign countries outside the camp, i.e. six shares for each citing paper. In columns from (3) to (8) the Table only reports estimates for frontier research, although the regressions control for non-frontier times post 1914 indicators. For the results reported in columns (3)-(4), frontier research is defined as research that ended up in the top 5% of the subject-level citation distribution until today. Similarly, for the results reported in columns (5)-(6) (and (7)-(8)), frontier research is defined as research that ended up in the top 3% (1%) of the subject-level citation distribution until today. We count citations to recent research, i.e. research published in the preceding five years, e.g. 1901-1905 for citing papers published in 1905, 1902-1906 for citing papers published in 1906, and so on. The reference/omitted category in columns (1)-(2) (and (3) to (8)) is the citation share to (frontier) research from home *inclusive* of self-citations. Standard errors are clustered at the country-times-field level. Significance levels: *** p<0.01, ** p<0.05, and * p<0.1. The data were collected by the authors and combine scientist census data from *Minerva - Handbuch der Gelehrten Welt* and publication and citation data from *ISI - Web of Science* (see section 2 for details).

Table A.8:
Changes in International Citations: Alternative Definitions of Recent Research

Dependent variable:	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Citation Shares to recent research	Research published in previous 3 years				Research published in previous 10 years			
Foreign *outside* camp × Post 1914	-0.210***	-0.276***			-0.206***	-0.221***		
	(0.035)	(0.048)			(0.029)	(0.037)		
Foreign *outside* camp × WWI			-0.242***	-0.239***			-0.190***	-0.190***
			(0.029)	(0.042)			(0.023)	(0.033)
Foreign *outside* camp × Boycott			-0.232***	-0.226***			-0.234***	-0.233***
			(0.036)	(0.064)			(0.031)	(0.053)
Foreign *outside* camp × Post Boycott			-0.184***	-0.176***			-0.190***	-0.188***
			(0.045)	(0.064)			(0.038)	(0.054)
Foreign *inside* camp × Post 1914	-0.063	-0.152***			-0.077**	-0.127***		
	(0.040)	(0.055)			(0.035)	(0.045)		
Foreign *inside* camp × WWI			-0.110***	-0.152***			-0.096***	-0.116***
			(0.039)	(0.050)			(0.032)	(0.043)
Foreign *inside* camp × Boycott			-0.074*	-0.158**			-0.095**	-0.142**
			(0.042)	(0.063)			(0.038)	(0.062)
Foreign *inside* camp × Post Boycott			-0.039	-0.158**			-0.057	-0.128**
			(0.047)	(0.063)			(0.040)	(0.064)
Paper FE	YES	YES	YES	YES	YES	YES	YES	YES
Camp FE	YES	YES	YES	YES	YES	YES	YES	YES
Foreign *in/outside* time trends		YES		YES		YES		YES
Observations	83,160	83,160	83,160	83,160	117,486	117,486	117,486	117,486
Number of citing papers	27,720	27,720	27,720	27,720	39,162	39,162	39,162	39,162
Within R-squared	0.340	0.341	0.341	0.341	0.326	0.326	0.327	0.327

Notes: Each column reports one set of parameter estimates of regression (1) for citing papers published between 1905 and 1930. The dependent variable measures the share of references to research by scientists from home, foreign countries inside the camp, and foreign countries outside the camp. We focus on citations to recent research: in columns (1)-(4) research published in the preceding 3 years and in columns (5)-(8) research published in the preceding 10 years. The reference/omitted category is the citation share to research from home. Standard errors are clustered at the country-times-field level. Significance levels: ∗∗∗ p<0.01, ∗∗ p<0.05, and ∗ p<0.1. The data were collected by the authors and combine scientist census data from *Minerva - Handbuch der Gelehrten Welt* and publication and citation data from *ISI - Web of Science* (see section 2 for details).

Table A.9:
INTERNATIONAL CITATIONS: ALL PRE-WWI COHORTS

Dependent variable: *Citation Shares to cohort*	(1) *1903-05*	(2) *1904-06*	(3) *1905-07*	(4) *1906-08*	(5) *1907-09*	(6) *1908-10*	(7) *1909-11*	(8) *1910-12*	(9) *1911-13*
Foreign *outside* camp × Post 1914	0.120***	0.0826***	0.0509*	0.0188	0.0429	0.0502	0.0354	0.0300	0.0422
	(0.0286)	(0.0276)	(0.0290)	(0.0257)	(0.0285)	(0.0310)	(0.0333)	(0.0302)	(0.0268)
Foreign *inside* camp × Post 1914	0.200***	0.179***	0.148***	0.117***	0.125***	0.119***	0.0980***	0.0814***	0.0737**
	(0.0509)	(0.0470)	(0.0373)	(0.0353)	(0.0308)	(0.0261)	(0.0249)	(0.0235)	(0.0286)
Paper FE	YES	YES	YES	YES	YES	YES	YES	YES	YES
Camp FE	YES	YES	YES	YES	YES	YES	YES	YES	YES
Observations	18,870	19,896	21,963	24,735	27,081	28,254	29,358	31,242	32,445
Number of citing papers	6,290	6,632	7,321	8,245	9,027	9,418	9,786	10,414	10,815
Within R-squared	0.113	0.133	0.145	0.144	0.129	0.130	0.135	0.157	0.187

Notes: Each column reports one set of parameter estimates of regression (1) for citing papers published between the first year of the relevant cohort and 1930. The dependent variable measures the share of references to a three year cohort of research by scientists from home, foreign countries inside the camp, and foreign countries outside the camp. We measure citations to a *fixed cohort* of research published between 1903 and 1905 in column (1), between 1904 and 1906 in column (2), and so on. The reference/omitted category is the share of references to the relevant cohort of research from home. Standard errors are clustered at the country-times-field level. Significance levels: *** p<0.01, ** p<0.05, and * p<0.1. The data were collected by the authors and combine scientist census data from *Minerva - Handbuch der Gelehrten Welt* and publication and citation data from *ISI - Web of Science* (see section 2 for details).

Table A.10:
CHANGES IN INTERNATIONAL CITATIONS: NEUTRALS

Dependent variable: *Neutral Cit. Sh. to recent research*	(1)	(2)	(3)	(4)
Foreign *outside* camp × Post 1914	-0.060	-0.074		
	(0.041)	(0.077)		
Allied camp × Post 1914			0.107**	0.010
			(0.052)	(0.068)
Central camp × Post 1914			-0.195***	-0.096
			(0.045)	(0.072)
Foreign *inside* camp × Post 1914	0.009	0.100*	0.009	0.100*
	(0.024)	(0.054)	(0.024)	(0.054)
Paper FE	YES	YES	YES	YES
Camp FE	YES	YES	YES	YES
Camp-specific time trends		YES		YES
Observations	5,865	5,865	9,775	9,775
Number of citing papers	1,955	1,955	1,955	1,955
Within R-squared	0.528	0.528	0.206	0.209

Notes: Each column reports one set of parameter estimates of regression (1) for Neutral citing papers published between 1905 and 1930. In columns (1) and (2) the dependent variable measures citation shares to research produced by scientists from home, foreign scientists inside the camp, and foreign scientists outside the camp. The dependent variable in columns (3) and (4) further splits the share of references to research from foreign scientists outside the camp into Allied, Central, and Other (not reported in the table). We count citations to recent research, i.e. research published in the preceding five years. The reference/omitted category is the Neutral citation share to research from home. Standard errors are clustered at the country-times-field level. Significance levels: *** p<0.01, ** p<0.05, and * p<0.1. The data were collected by the authors and combine scientist census data from *Minerva - Handbuch der Gelehrten Welt* and publication and citation data from the *ISI - Web of Science* (see section 2 for details).

Table A.11:
THE SIMILARITY OF PAPERS AS MEASURED BY LATENT SEMANTIC ANALYSIS: ROBUSTNESS CHECKS

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Dependent variable:	Most similar title		Average 5 most similar titles		Most similar title		Average 5 most similar titles	
LSA Title Similarity to recent papers	300 Components				1000 Components			
Foreign *outside* camp × Post 1914	-0.426***		-0.564***		-0.506***		-0.634***	
	(0.091)		(0.117)		(0.095)		(0.136)	
Foreign *outside* camp × WWI		-0.438***		-0.561***		-0.501***		-0.618***
		(0.080)		(0.106)		(0.085)		(0.121)
Foreign *outside* camp × Boycott		-0.490***		-0.642***		-0.575***		-0.704***
		(0.110)		(0.134)		(0.107)		(0.152)
Foreign *outside* camp × Post Boycott		-0.378***		-0.510***		-0.459***		-0.591***
		(0.091)		(0.120)		(0.102)		(0.141)
Foreign *inside* camp × Post 1914	0.086		0.102		0.039		0.033	
	(0.155)		(0.189)		(0.147)		(0.190)	
Foreign *inside* camp × WWI		0.019		-0.023		-0.045		-0.087
		(0.150)		(0.178)		(0.131)		(0.174)
Foreign *inside* camp × Boycott		0.019		0.043		-0.005		-0.014
		(0.164)		(0.199)		(0.159)		(0.200)
Foreign *inside* camp × Post Boycott		0.154		0.184		0.096		0.104
		(0.155)		(0.191)		(0.147)		(0.194)
Paper FE	YES	YES	YES	YES	YES	YES	YES	YES
Camp FE	YES	YES	YES	YES	YES	YES	YES	YES
Observations	71,586	71,586	71,586	71,586	71,586	71,586	71,586	71,586
Number of citing papers	23,862	23,862	23,862	23,862	23,862	23,862	23,862	23,862
Within R-squared	0.144	0.146	0.214	0.216	0.174	0.175	0.242	0.243

Notes: Each column reports one set of parameter estimates of regression (1) for papers published between 1905 and 1930. The dependent variable measures the standardized (i.e., mean 0 and standard deviation 1) LSA title similarity to papers by scientists from home, foreign countries inside the camp, and foreign countries outside the camp. In columns (1)-(4) LSA title similarity is based on 300 components. In columns (5)-(8) LSA title similarity is based on 1000 components. In columns (1), (2), (5), and (6), LSA title similarity is computed as the similarity of the most similar title from each camp. In columns (3), (4), (7), and (8), LSA title similarity is computed as the average similarity of the five most similar titles from each camp. We compute the title similarity to recent papers, i.e. papers published in the preceding five years, e.g. 1901-1905 for papers published in 1905. The reference/omitted category is the LSA title similarity to papers from home. Standard errors are clustered at the country-times-field level. Significance levels: $***$ p<0.01, $**$ p<0.05, and $*$ p<0.1. The data were collected by the authors and combine scientist census data from *Minerva - Handbuch der Gelehrten Welt* and publication and citation data from *ISI - Web of Science* (see section 2 for details).

Table A.12:
YEARLY EFFECT ON PUBLICATIONS

	Par. Est.	Std. Er.		Par. Est.	Std. Er.
Pre-war rel. on 1% front. *OUT*×1905	-0.937	1.238	Pre-war rel. on 1% front. *IN*×1905	-0.233	1.544
Pre-war rel. on 1% front. *OUT*×1906	-2.073	0.989	Pre-war rel. on 1% front. *IN*×1906	0.106	1.156
Pre-war rel. on 1% front. *OUT*×1907	-0.496	1.178	Pre-war rel. on 1% front. *IN*×1907	0.215	1.011
Pre-war rel. on 1% front. *OUT*×1908	-1.751	1.059	Pre-war rel. on 1% front. *IN*×1908	-0.062	0.921
Pre-war rel. on 1% front. *OUT*×1909	-0.711	0.792	Pre-war rel. on 1% front. *IN*×1909	1.960	0.602
Pre-war rel. on 1% front. *OUT*×1910	-1.490	0.705	Pre-war rel. on 1% front. *IN*×1910	-0.282	0.626
Pre-war rel. on 1% front. *OUT*×1911	-0.074	0.892	Pre-war rel. on 1% front. *IN*×1911	1.681	0.717
Pre-war rel. on 1% front. *OUT*×1912	-1.204	0.844	Pre-war rel. on 1% front. *IN*×1912	-0.848	0.589
Pre-war rel. on 1% front. *OUT*×1914	-2.111	0.862	Pre-war rel. on 1% front. *IN*×1914	0.371	0.452
Pre-war rel. on 1% front. *OUT*×1915	-3.499	1.030	Pre-war rel. on 1% front. *IN*×1915	0.660	1.056
Pre-war rel. on 1% front. *OUT*×1916	-3.109	0.913	Pre-war rel. on 1% front. *IN*×1916	-0.061	0.988
Pre-war rel. on 1% front. *OUT*×1917	-3.452	1.045	Pre-war rel. on 1% front. *IN*×1917	-0.655	1.225
Pre-war rel. on 1% front. *OUT*×1918	-3.192	0.834	Pre-war rel. on 1% front. *IN*×1918	-1.135	1.004
Pre-war rel. on 1% front. *OUT*×1919	-2.186	0.808	Pre-war rel. on 1% front. *IN*×1919	-0.299	0.811
Pre-war rel. on 1% front. *OUT*×1920	-2.417	0.805	Pre-war rel. on 1% front. *IN*×1920	-0.648	0.719
Pre-war rel. on 1% front. *OUT*×1921	-2.405	0.687	Pre-war rel. on 1% front. *IN*×1921	-1.040	0.669
Pre-war rel. on 1% front. *OUT*×1922	-2.732	0.965	Pre-war rel. on 1% front. *IN*×1922	-1.708	0.950
Pre-war rel. on 1% front. *OUT*×1923	-1.901	0.755	Pre-war rel. on 1% front. *IN*×1923	-0.485	0.640
Pre-war rel. on 1% front. *OUT*×1924	-2.173	0.895	Pre-war rel. on 1% front. *IN*×1924	-0.870	0.835
Pre-war rel. on 1% front. *OUT*×1925	-2.348	0.751	Pre-war rel. on 1% front. *IN*×1925	-1.120	0.832
Pre-war rel. on 1% front. *OUT*×1926	-2.937	1.019	Pre-war rel. on 1% front. *IN*×1926	-0.898	0.717
Pre-war rel. on 1% front. *OUT*×1927	-3.471	0.974	Pre-war rel. on 1% front. *IN*×1927	-0.788	1.054
Pre-war rel. on 1% front. *OUT*×1928	-2.805	0.969	Pre-war rel. on 1% front. *IN*×1928	-0.467	0.912
Pre-war rel. on 1% front. *OUT*×1929	-2.263	0.743	Pre-war rel. on 1% front. *IN*×1929	0.030	0.838
Pre-war rel. on 1% front. *OUT*×1930	-2.237	0.863	Pre-war rel. on 1% front. *IN*×1930	0.482	1.041
Scientist FE			YES		
Year FE			YES		
Pre-war reliance on non-frontier			YES		
Career age × field interactions			YES		
Observations			227,084		
Number of scientists			8,734		

Notes: The Table plots parameter estimates from regression (4). "Pre-war rel. on 1% front. *OUT*" reports point estimates ($\beta_{1\tau}$) that measure changes in yearly publications for scientists in field-country pairs that, in the pre-war period, relied on top 1% research from outside the camp, compared to scientists who relied on top 1% research from home. "Pre-war rel. on 1% front. *IN*" reports point estimates ($\beta_{2\tau}$) that measure changes in yearly publications for scientists in field-country pairs that, in the pre-war period, relied on top 1% research from foreign scientists inside the camp, compared to scientists who relied on top 1% research from home. Pre-war reliance on top 1% research is measured by pre-war citations to top 1% research at the field-country pair level. Top 1% research is defined as research that ended up in the top 1% of the subject-level citation distribution, counting citations until today. The regression also controls for pre-war reliance on non-frontier research from each camp interacted with year indicators. The data were collected by the authors and combine scientist census data from *Minerva - Handbuch der Gelehrten Welt* and publication and citation data from *ISI - Web of Science* (see section 2 for details).

Table A.13:
EFFECT ON PUBLICATIONS: DIFFERENT COUNTRY-FIELD THRESHOLDS

Dependent variable: *Number of publications*	(1) 5 paper threshold	(2) 10 paper threshold
Panel A: Frontier measured by Top 1%		
Pre-war reliance on 1% frontier *OUT*	-1.727***	-1.872***
× Post 1914	(0.638)	(0.669)
Pre-war reliance on 1% frontier *IN*	-0.827	-0.850
× Post 1914	(0.736)	(0.772)
Within R-squared	0.062	0.062
Panel B: Frontier measured by Top 3%		
Pre-war reliance on 3% frontier *OUT*	-0.784***	-0.761**
× Post 1914	(0.282)	(0.306)
Pre-war reliance on 3% frontier *IN*	-0.363	-0.309
× Post 1914	(0.283)	(0.377)
Within R-squared	0.062	0.062
Panel C: Frontier measured by Top 5%		
Pre-war reliance on 5% frontier *OUT*	-0.380*	-0.265
× Post 1914	(0.220)	(0.245)
Pre-war reliance on 5% frontier *IN*	-0.152	-0.150
× Post 1914	(0.218)	(0.281)
Within R-squared	0.062	0.062
Scientist FE	YES	YES
Year FE	YES	YES
Pre-war reliance on non-frontier	YES	YES
Career age × field interactions	YES	YES
Observations	227,084	220,688
Number of scientists	8,734	8,488

Notes: Each column and each panel reports one set of parameter estimates of regression (3) for the panel of university scientists between 1905 and 1930. We show robustness to changing the minimum number of publications that scientists from a certain country-field pair published between 1905-1913 to compute the pre-war reliance on home and foreign research. In column (1), we report the baseline specification with the minimum number of pre-war publications equal to 5. In column (2), we increase the minimum number of pre-war publications to 10 and drop scientists in country-field pairs with fewer than 10 pre-war papers. The dependent variable measures the yearly number of publications in the 160 top journals in our data. "Pre-war reliance on frontier *OUT*" is the pre-war citation share to frontier research (1%, 3%, or 5%) from outside the camp. "Pre-war reliance on frontier *IN*" is the pre-war citation share to frontier research (1%, 3%, or 5%) from foreign countries inside the camp. The reference/omitted category is "Pre-war reliance on frontier *HOME*." Standard errors are clustered at the country-times-field level. Significance levels: *** p<0.01, ** p<0.05, and * p<0.1. The data were collected by the authors and combine scientist census data from *Minerva - Handbuch der Gelehrten Welt* and publication and citation data from *ISI - Web of Science* (see section 2 for details).

Table A.14:
Death During WWI And Dependence on Foreign Research

Dependent variable: *Indicator for Death between 1914 and 1918*	(1) Frontier: 1%	(2) Frontier: 3%	(3) Frontier: 5%
Pre-war reliance on frontier *OUT*	0.117	0.027	-0.010
	(0.122)	(0.088)	(0.083)
Pre-war reliance on frontier *IN*	0.260	0.156	0.190
	(0.359)	(0.201)	(0.123)
Pre-war reliance on non-frontier	YES	YES	YES
Career age × field interactions	YES	YES	YES
Number of scientists	8,734	8,734	8,734
Within R-squared	0.013	0.014	0.015

Notes: Each column reports parameter estimates of a regression of an indicator variable that is equal to 1 if a scientist died between 1914 and 1918 and 0 otherwise on the pre-war reliance on frontier research from outside the camp and inside the camp for our sample of university scientists. "Pre-war reliance on frontier *OUT*" is the pre-war citation share to frontier research (1%, 3%, or 5%) from outside the camp. "Pre-war reliance on frontier *IN*" is the pre-war citation share to frontier research (1%, 3%, or 5%) from foreign countries inside the camp. The reference/omitted category is "Pre-war reliance on frontier *HOME*." Standard errors are clustered at the country-times-field level. Significance levels: $***$ p<0.01, $**$ p<0.05, and $*$ p<0.1. The data were collected by the authors and combine scientist census data from *Minerva - Handbuch der Gelehrten Welt*, publication and citation data from *ISI - Web of Science*, and obituary data from various sources (see Appendix section E.6 for details).

Table A.15:
EFFECT ON NOVEL SCIENTIFIC WORDS: ROBUSTNESS

	(1)	(2)	(3)	(4)	(5)	(6)
	Novel scientific words		Novel scientific words		Novel scientific words	
Dependent Variable:	5,000 stopwords		15,000 stopwords		36,662 stopwords	
Panel A: Frontier measured by Top 1%						
Pre-war reliance on 1% frontier *OUT*	-1.239**	-0.787**	-1.181***	-0.759**	-0.985**	-0.471*
× Post 1914	(0.471)	(0.354)	(0.430)	(0.316)	(0.394)	(0.276)
Pre-war reliance on 1% frontier *IN*	-0.852*	-0.875**	-0.996**	-1.007***	-0.894**	-0.866***
× Post 1914	(0.486)	(0.386)	(0.433)	(0.341)	(0.393)	(0.278)
Within R-squared	0.026	0.030	0.023	0.027	0.019	0.022
Panel B: Frontier measured by Top 3%						
Pre-war reliance on 3% frontier *OUT*	-0.332	-0.360*	-0.286	-0.348**	-0.243	-0.261
× Post 1914	(0.267)	(0.182)	(0.265)	(0.174)	(0.248)	(0.160)
Pre-war reliance on 3% frontier *IN*	-0.116	-0.150	-0.179	-0.207	-0.208	-0.227
× Post 1914	(0.230)	(0.175)	(0.217)	(0.159)	(0.195)	(0.137)
Within R-squared	0.026	0.030	0.023	0.027	0.019	0.022
Panel C: Frontier measured by Top 5%						
Pre-war reliance on 5% frontier *OUT*	-0.210	-0.297*	-0.162	-0.305*	-0.137	-0.240
× Post 1914	(0.205)	(0.170)	(0.205)	(0.159)	(0.200)	(0.150)
Pre-war reliance on 5% frontier *IN*	-0.133	-0.127	-0.160	-0.160	-0.178	-0.172
× Post 1914	(0.175)	(0.137)	(0.162)	(0.126)	(0.154)	(0.120)
Within R-squared	0.026	0.030	0.023	0.027	0.019	0.022
Scientist FE	YES	YES	YES	YES	YES	YES
Year FE	YES		YES		YES	
Pre-war reliance on non-frontier	YES	YES	YES	YES	YES	YES
Career age × field interactions	YES	YES	YES	YES	YES	YES
Camp × field × year FE		YES		YES		YES
Observations	227,084	227,084	227,084	227,084	227,084	227,084
Number of scientists	8,734	8,734	8,734	8,734	8,734	8,734

Notes: Each column and each panel reports one set of parameter estimates of regression (3) for the panel of university scientists between 1905 and 1930. In all columns, the dependent variable counts the number of novel words that appeared in the title of a scientific paper. "Pre-war reliance on frontier *OUT*" is the pre-war citation share to frontier research (1%, 3%, or 5%) from outside the camp. "Pre-war reliance on frontier *IN*" is the pre-war citation share to frontier research (1%, 3%, or 5%) from foreign countries inside the camp. The reference/omitted category is "Pre-war reliance on frontier *HOME*." Standard errors are clustered at the country-times-field level. Significance levels: *** p<0.01, ** p<0.05, and * p<0.1. The data were collected by the authors and combine scientist census data from *Minerva - Handbuch der Gelehrten Welt* and publication and citation data from *ISI - Web of Science*.

Table A.16:
Effect on Patent-Relevant Words: Robustness

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Dependent Variable:	Patent relevant words 5,000 stopwords		Patent relevant words 15,000 stopwords		Patent relevant words 36,662 stopwords		Patent relevant words not winsorized		Patent relevant words patents counted once		Patent relevant words all patents, 1920-79	
Panel A: Frontier measured by Top 1%												
Pre-war reliance on 1% frontier *OUT*	-0.916**	-0.968***	-1.218***	-1.319***	-0.808***	-0.723**	-0.564**	-0.984***	-1.058***	-1.135***	-1.079***	-1.050***
× Post 1914	(0.366)	(0.315)	(0.340)	(0.287)	(0.289)	(0.281)	(0.232)	(0.213)	(0.349)	(0.293)	(0.364)	(0.312)
Pre-war reliance on 1% frontier *IN*	-0.272	-0.436	-0.774***	-0.944***	-0.574**	-0.655***	-0.353*	-0.663***	-0.533*	-0.642**	-0.548*	-0.590**
× Post 1914	(0.336)	(0.266)	(0.237)	(0.211)	(0.280)	(0.242)	(0.193)	(0.167)	(0.300)	(0.256)	(0.315)	(0.273)
Within R-squared	0.016	0.020	0.014	0.017	0.010	0.013	0.001	0.003	0.015	0.019	0.019	0.022
Panel B: Frontier measured by Top 3%												
Pre-war reliance on 3% frontier *OUT*	-0.356*	-0.517***	-0.456**	-0.692***	-0.355*	-0.442**	-0.314**	-0.539***	-0.399**	-0.631***	-0.378*	-0.566***
× Post 1914	(0.193)	(0.163)	(0.218)	(0.170)	(0.194)	(0.175)	(0.129)	(0.126)	(0.198)	(0.155)	(0.213)	(0.188)
Pre-war reliance on 3% frontier *IN*	0.015	-0.001	-0.204	-0.224*	-0.195	-0.245*	-0.121	-0.127*	-0.118	-0.134	-0.068	-0.074
× Post 1914	(0.183)	(0.153)	(0.174)	(0.127)	(0.191)	(0.141)	(0.093)	(0.076)	(0.184)	(0.146)	(0.190)	(0.160)
Within R-squared	0.016	0.020	0.014	0.017	0.010	0.013	0.001	0.003	0.015	0.019	0.019	0.022
Panel C: Frontier measured by Top 5%												
Pre-war reliance on 5% frontier *OUT*	-0.323**	-0.431***	-0.323*	-0.581***	-0.239	-0.393***	-0.230**	-0.450***	-0.335**	-0.546***	-0.317*	-0.502***
× Post 1914	(0.150)	(0.156)	(0.172)	(0.150)	(0.155)	(0.139)	(0.102)	(0.141)	(0.156)	(0.145)	(0.172)	(0.183)
Pre-war reliance on 5% frontier *IN*	-0.074	-0.081	-0.164	-0.196**	-0.195	-0.241**	-0.062	-0.091	-0.143	-0.172	-0.104	-0.117
× Post 1914	(0.131)	(0.108)	(0.124)	(0.093)	(0.137)	(0.113)	(0.093)	(0.084)	(0.137)	(0.107)	(0.141)	(0.118)
Within R-squared	0.016	0.020	0.014	0.017	0.010	0.013	0.001	0.003	0.015	0.019	0.019	0.022
Scientist FE	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Year FE	YES		YES		YES		YES		YES		YES	
Pre-war reliance on non-frontier	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Career age × field interactions	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Camp × field × year FE		YES		YES		YES		YES		YES		YES
Observations	227,084	227,084	227,084	227,084	227,084	227,084	227,084	227,084	227,084	227,084	227,084	227,084
Number of scientists	8,734	8,734	8,734	8,734	8,734	8,734	8,734	8,734	8,734	8,734	8,734	8,734

Notes: Each column and each panel reports one set of parameter estimates of regression (3) for the panel of university scientists. In columns (1)-(8), the dependent variable counts the number of times a novel word published in a scientific paper in year t was used in the text of patents granted by the U.S. Patent Office in years *t+15* and *t+30*. In columns (9)-(10), the dependent variable counts the number of patents in which a novel word published in a scientific paper in year t was used by patents granted in years *t+15* and *t+30*. In columns (11) and (12), the dependent variable counts the number of times a novel word published in a scientific paper was used in the text of any patent granted between the publication date of the paper (or 1920 if the paper was published earlier) and 1979. In columns (1)-(6) and (9)-(12), the dependent variable is winsorized at the 99th percentile. "Pre-war reliance on frontier *OUT*" is the pre-war citation share to frontier research (1%, 3%, or 5%) from outside the camp. "Pre-war reliance on frontier *IN*" is the pre-war citation share to frontier research (1%, 3%, or 5%) from foreign countries inside the camp. The reference/omitted category is "Pre-war reliance on frontier *HOME*." Standard errors are clustered at the country-times-field level. Significance levels: $***$ p<0.01, $**$ p<0.05, and $*$ p<0.1. The data were collected by the authors and combine scientist census data from *Minerva - Handbuch der Gelehrten Welt*, publication and citation data from *ISI - Web of Science*, and patent data from the *U.S. Patent Office* (see section 2 for details).

B Additional Results Section 3

B.1 Heterogeneity Allied and Central Papers

We also explore heterogeneity in effects on citation shares between Allied and Central citing papers. We find that the results are stronger for Allied citing papers than for Central citing paper during WWI. During the boycott, the interruption of knowledge flows had an almost symmetric effect on citation shares in the two camps (appendix Table A.6, columns 2 and 3).

B.2 Robustness Checks on International Knowledge Flows

The main results in section 3.1 are estimated on the full sample of papers. The sample includes papers by scientists with a university position by 1914 and papers by other scientists if they reported a university affiliation in the paper (see section 2 for details). If new citing scientists had different research practices that resulted in different citation patterns, then the entry of citing scientists who reported an affiliation in the paper could potentially affect our findings. To test for this possibility, we restrict the sample of citing scientists to those with a university position by 1914. The initial decline in the share of references quoting research from outside the camp was similar to the decline in the full sample; the recovery during the mid-1920s, however, was stronger (appendix Figure A.6, panel a).

For the results reported in appendix Figure A.6, panel (a), we investigate citations of established scientists and consider references to any research, independently of whether the research was produced by established scientists or by other scientists. If other scientists worked on different topics and entered the sample at differential rates across camps, the changes in citation patterns could be driven by the changing composition of research produced at home or abroad. We test for this possibility by investigating changes in citation shares of established scientists and by considering only references to research by other established scientists. The relative decline of references to research from *outside* the camp was similar to that of the full sample, but there was full recovery in these citation shares toward the end of the sample period (appendix Figure A.6, panel b). The relative decline of references to research from foreign scientists *inside* the camp was smaller for this sample, and exhibited a stronger pre-trend. Differently from the citation patterns reported for the full sample of scientists (Figure IV), established scientists went back to their pre-war citation behavior. This suggests that researchers that entered science during the war and the boycott were permanently less international than the established scientists.

Finally, we investigate how changes in the number of papers that were produced in each camp affected the citation patterns. For this test, we normalize the citation shares by the total number of potentially citeable papers produced in each camp. We divide the citation shares to research from home by the number of potentially citeable papers produced at home. Similarly, we normalize the citation shares to foreign research produced inside the camp and outside the camp with the number of potentially citeable papers in the two camps.[45] The normalized citation shares to research from outside the camp fell after 1914, particularly during the early boycott years (Figure A.6, panel c). By the mid-1920s, the normalized shares fully recovered. The normalized citation shares to research from foreign scientists inside the camp also fell, but less sharply than the outside-camp shares. In any given year, scientists in small countries did not publish many papers in one of the 160 top journals. As a result, the normalized citation shares to research from home (the excluded category in the regression) fluctuated substantially for the smaller countries, leading to relatively large variability of the results plotted in Figure A.6, panel (c). We therefore re-estimate the regressions with the normalized citation shares for the six countries with the largest scientific output in our data. The results are indeed less volatile and confirm the previous findings (Figure A.6, panel d).[46]

B.3 The Effect of WWI and the Boycott on Relative Citations of Neutrals

Our data also allow us to investigate the effect of WWI and the boycott on citation patterns of Neutrals by estimating equations (1) and (2) for Neutral papers. For these, foreign inside camp research was produced in other Neutral countries and foreign outside camp research was produced outside the Neutral camp.

Not surprisingly, citation shares to research from outside the camp were always very high because none of the Neutral countries was very large, and hence Neutral scientists relied on research from the leading scientific nations. After 1914, there was only a small, but not significant, decline in the citation shares to research from outside the camp. There was no decline in the citation shares to foreign research from inside the camp (appendix Figure A.8, panel (a) and appendix Table A.10 columns 1 and 2).

The citation shares to research from outside the camp can be divided into the citation shares to Allied, Central, and other research. During the war and the boycott, Neutral papers increased the citation shares to Allied research and decreased the citation shares to Central research (appendix Figure A.8, panel (b) and appendix Table A.10 columns 3 and 4). These results are consistent with historical anecdotes that Neutral scientists could still attend Allied conferences and that Germany

[45]We compute the normalized citation shares to research produced at home as: $(\frac{c_{Home}}{C_{Total}} \times \frac{1}{N_{Home}})$, where N_{Home} is the number of potentially citeable papers produced at home in the five years preceding the publication of the citing paper. Similarly, we compute the normalized shares $(\frac{c_{Foreign-IN}}{C_{Total}} \times \frac{1}{N_{Foreign-IN}})$ and $(\frac{c_{Foreign-OUT}}{C_{Total}} \times \frac{1}{N_{Foreign-OUT}})$. The normalized shares can be interpreted as the probability that a reference quotes a randomly selected paper produced in a certain camp. As we divide the citation shares by thousands of potentially citeable papers, the measure has a lower scale than before.

[46]In further robustness checks, we show that the results also hold when we restrict the sample to citing papers of scientists from small scientific countries and when we separate citation shares to research from outside the camp into the shares to research from enemy countries, Neutral countries, and other countries (appendix Figure A.7)

restricted the delivery of scientific journals even to Neutral countries during WWI (Reinbothe, 2006, pp. 116).

C Appendix Latent Semantic Analysis

Latent Semantic Analysis is a machine learning technique which was developed for information retrieval in search queries (Deerwester et al., 1990). In search queries, it is important to accurately judge the semantic relationships between words and documents to provide coherent search results. LSA has been shown to be reliable in many other task involving word/text similarity (Landauer et al., 1998). What makes these similarity tasks challenging is that there are many different ways to express the same idea. LSA "learns" the relationships between words. LSA accomplishes this by using Truncated Singular Value Decomposition, which reduces the dimensionality of the semantic space.

LSA requires a document-term-matrix A with dimensions $D \times V$ as input. V is the number of unique terms, i.e. words, in the vocabulary and D is the number of documents, i.e. paper titles. A contains a row for each document, while the columns contain the term counts. Defining $f_{d,v}$ as the number of times term v appears in document d, the matrix A is given by:

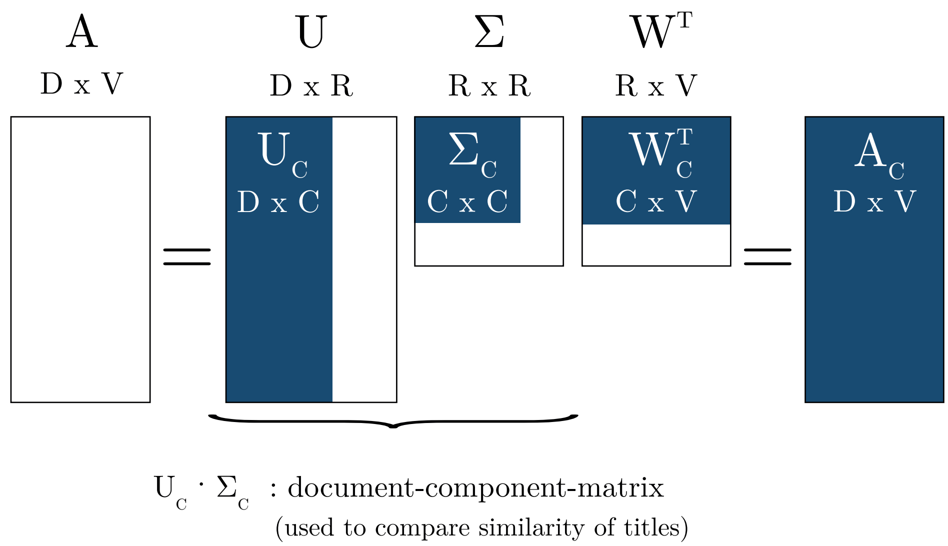
$$\underbrace{A}_{D\times V} = \begin{pmatrix} f_{1,1} & \cdots & f_{1,d} \\ \vdots & \ddots & \vdots \\ f_{d,1} & \cdots & f_{d,v} \end{pmatrix}$$

To improve the performance of LSA, we re-weigh the entries in A using term frequency–inverse document frequency (tf-idf). Tf-idf re-weighting replaces $f_{d,v}$ by $tf - idf(f_{d,v}) = \big(1 + \log(f_{d,v})\big) \cdot \left(\log\left(\frac{1+D}{1+d_v}\right) + 1\right)$, where d_v is the number of documents term v appears in at least once. This step decreases the weights of words which appear frequently in all documents D, since these words contribute little to the meaning of documents.[47]

LSA decomposes matrix A with $rank(A) = R$ into three matrices such that $A = U\Sigma W^T$, where U is a $D \times R$ orthogonal matrix, W^T is a $R \times V$ orthogonal matrix, and Σ is a $R \times R$ diagonal matrix. LSA truncates the dimensions of the matrices until U becomes U_C of dimension $D \times C$, Σ becomes Σ_C of dimension $C \times C$, and W^T becomes W_C^T of dimension $C \times V$ (see appendix Figure C.1).

[47]Theoretically, one could compare the similarity between two titles using just the individual word frequencies or tf-idf scores in each title. Differently from LSA, the use of word-frequencies would ignore relationships between words.

Figure C.1:
LSA Graphical Representation



Notes: The Figure is a modification of the graphic in Martin and Berry (2007)

C is the user-chosen number of components, which is chosen on the basis of the size of the vocabulary. During the truncation process, LSA removes rows and columns associated with the smallest values in the matrix Σ. This gives the best rank-C approximation A_C of the original matrix A. The output of LSA is $U_C\Sigma_C$, a $D \times C$ document-component matrix that is used to compare the similarity of documents.

LSA reduces the components of the semantic space to the C most important ones and therefore uncovers latent semantic connections between words.[48]

For our main results, we choose $C = 500$ components. For most applications, $100 \leq C \leq 1000$ leads to good results (Martin and Berry, 2007). Our results are robust to using either 300 or 1000 components. To implement LSA, we use Python machine learning library *scikit learn (Pedregosa et al., 2011).*

D Stylized Example of Identifying Variation for Productivity Regressions

The identifying variation to estimate regression equation (3) relies on field-country level differences in citations to research from home, foreign countries inside the camp, and outside the camp.

[48]The LSA process is conceptually similar to a principal component analysis for regressions. Instead of reducing the number of regressors, it reduces the number of components in semantic space.

D.1 Model with Scientist Fixed Effects

The estimation of the baseline model (equation (3)) with scientist fixed effects only requires field-country level differences in output as a source of variation (for an example, see Panel B of Table D.1; the example abstracts from the distinction between frontier and non-frontier research and from the distinction between fields in each country).[49] It is easily observable that countries differ substantially in the amount of research that they produce, especially frontier research.[50]

D.2 Model with Scientist Fixed Effects and Camp-times-Field-times-Year Fixed Effects

The estimation of β_2 in the augmented model that additionally includes camp-times-field-times-year fixed effects only requires the field-country level differences in output described above (see Panel B of Table D.1). Cross-country frictions to knowlege flows within fields, which occur even in normal times, can be exploited to estimate β_1 in the augmented model. Specifically, frictions to knowledge flows within the camp and differential output across countries (within fields) lead to within camp variation in citation shares to research from outside the camp (see Panel C of Table D.1).[51]

Examples of such frictions, that occur even in normal times, are differences in languages, travel costs to attend seminars and conferences (e.g. Table II), and journal subscriptions that favored locally produced journals.

[49]The sum of all scientist fixed effects in a field-country pair are perfectly collinear to a field-country pair fixed effect.

[50]Only in the unrealistic case that all field-country pairs produced the same number of papers in the pre-war period, and knowledge travelled freely across countries, all field-country pairs would have the same citation shares to pre-war research and there would be no variation to estimate equation (3) (see Panel A of Table D.1).

[51]Panel D of Table D.1 shows the more realistic case of frictions both within and between camps. These frictions change pre-war citation shares, but are not necessary to introduce within-camp variation in citations shares to research from outside the camp. Any additional friction that varies at the country level (within fields) would introduce further within-camp variation in pre-war citation shares.

Table D.1: Stylized Example of Identifying Variation in Productivity Regressions

Panel A: Same output, no frictions

		Pre-war research cited by:				Resulting citation shares		
	Number of pre-war papers produced	U.S. biologists	U.K. biologists	German biologists	Austrian biologists	Home	Fout	Foin
USA biology	5	5	5	5	5	0.25	0.5	0.25
UK biology	5	5	5	5	5	0.25	0.5	0.25
Germany biology	5	5	5	5	5	0.25	0.5	0.25
Austria biology	5	5	5	5	5	0.25	0.5	0.25

Panel B: Different output, no frictions

		Pre-war research cited by:				Resulting citation shares		
	Number of pre-war papers produced	U.S. biologists	U.K. biologists	German biologists	Austrian biologists	Home	Fout	Foin
USA biology	10	10	10	10	10	0.40	0.40	0.20
UK biology	5	5	5	5	5	0.20	0.40	0.40
Germany biology	5	5	5	5	5	0.20	0.60	0.20
Austria biology	5	5	5	5	5	0.20	0.60	0.20

Panel C: Different output, frictions within the same camp

		Pre-war research cited by:				Resulting citation shares		
	Number of pre-war papers produced	U.S. biologists	U.K. biologists	German biologists	Austrian biologists	Home	Fout	Foin
USA biology	10	10	$10 \cdot 0.6 = 6$	10	10	0.43	0.43	0.13
UK biology	5	$5 \cdot 0.6 = 3$	5	5	5	0.24	0.48	0.29
Germany biology	5	5	5	5	$5 \cdot 0.6 = 3$	0.22	0.65	0.13
Austria biology	5	5	5	$5 \cdot 0.6 = 3$	5	0.22	0.65	0.13

Panel D: Different output, frictions both within and between camps

		Pre-war research cited by:				Resulting citation shares		
	Number of pre-war papers produced	U.S. biologists	U.K. biologists	German biologists	Austrian biologists	Home	Fout	Foin
USA biology	10	10	$10 \cdot 0.6 = 6$	$5 \cdot 0.6 = 3$	$5 \cdot 0.6 = 3$	0.53	0.32	0.16
UK biology	5	$5 \cdot 0.6 = 3$	5	$5 \cdot 0.6 = 3$	$5 \cdot 0.6 = 3$	0.29	0.35	0.35
Germany biology	5	$5 \cdot 0.6 = 3$	$5 \cdot 0.6 = 3$	5	$5 \cdot 0.6 = 3$	0.29	0.53	0.18
Austria biology	5	$5 \cdot 0.6 = 3$	$5 \cdot 0.6 = 3$	$5 \cdot 0.6 = 3$	5	0.29	0.53	0.18

Notes: The Table shows a stylized example of the identifying variation exploited to estimate equation (3). Panels C and D assume a proportional friction of $f = 0.6$. The results are qualitatively similar with any proportional friction $f \in (0, 1)$.

E Further Details on Data

E.1 Further Details on Journal Delay Data

We collect data on entry stamps from the Harvard library for four international journals. Two Central journals, the *Zeitschrift für Analytische Chemie* and the *Annalen der Physik*, and two Allied journals, the British journal *Nature*, and the French journal *Comptes Rendus Hebdomadaires des Séances de l'Académie des Sciences*. Appendix Table E.1, column 2, reports the volumes and issues for which we obtain entry stamps from the Harvard library. Sometimes two issues within a volume were published at the same time (e.g. no. 3 and 4) and hence they only have one entry stamp and one publication date. In very rare cases, the entry stamp is so blurred that the entry date is not legible.

At Harvard, we collect 61 (legible) entry stamps for the *Zeitschrift für Analytische Chemie*, 145 for the *Annalen der Physik*, 161 for *Nature*, and 28 for the *Comptes Rendus*.

Table E.1: Data Sources Journal Delays

(1)	(2)	(3)	(4)	(5)
Year reported in Figure (2)	Volume(s) at Harvard	Issues with stamps at Harvard	Issues with stamp at Heidelberg	Publication Dates
Panel (a): Zeitschrift für Analytische Chemie				
1910	49	all		10/27/1909 to 10/15/1910
1913	52	all		10/30/1912 to 09/17/1913
1917	56	all		11/30/1916 to 01/05/1918
1919	58	all		01/20/1919 to 01/22/1920
1921	60	all		12/15/1920 to 10/06/1921
1923	62	all		09/30/1922 to 05/20/1923
1927	71	all		04/14/1927 to 08/23/1927
Panel (b): Annalen der Physik				
1910	31-33	all	33:1	12/30/1909 to 12/20/1910
1913	40-42	all	40:1, 41:1, 42:1	12/31/1912 to 12/23/1913
1917	52-54	all	52:1, 53:1, 54:1	02/15/1917 to 04/26/1918
1919	58-60	all		01/17/1919 to 12/19/1919
1921	64-66	all	64:1-2, 65:1, 66:1	01/20/1921 to 12/20/1921
1923	70-72	all	70:1, 71:1, 72:1	01/18/1923 to 11/??/1923
1927	82-84	all	82:1, 83:1, 84:1	12/16/1926 to 01/13/1928
Panel (c): Nature				
1910	83	all		03/03/1910 to 06/30/1910
1913	91	all		03/06/1913 to 08/28/1913
1917	99	all		03/01/1917 to 08/30/1917
1919	103	all		03/06/1919 to 08/28/1919
1921	107	all		03/03/1921 to 08/25/1921
1923	111	all		01/06/1923 to 06/30/1923
1927	119	all		01/01/1927 to 03/26/1927
Panel (d): Comptes Rendus				
1910	150-151	1, 23, 10, 21		01/03/1910 to 11/21/1910
1913	156-157	7, 23, 8, 21		02/17/1913 to 11/24/1913
1917	164-165	7, 22, 8, 25		02/12/1917 to 12/17/1917
1919	168-169	3, 14, 26, 18		01/20/1919 to 11/03/1919
1921	172-173	2, 23, 15, 24		01/10/1921 to 12/12/1921
1923	176-177	10, 4, 19, 25		03/05/1923 to 12/17/1923
1927	184-185	7, 23, 7, 23		02/14/1927 to 12/05/1927

Notes: The Table reports volumes, issues, and publication dates for four international scientific journals. In contrast to all other issues, the last two 1923 issues in the *Annalen der Physik* only reported the month but not the day of publication. For these two issues, we set the publication dates to the middle of the month. The data were collected by the authors from the Harvard Library and the Library of the University of Heidelberg.

Depending on the journal and issue, either the publication date or editorial deadline is reported for each issue. The *Zeitschrift für Analytische Chemie* always reports editorial deadlines, the *Annalen der Physik* reports publication dates until 1923 and editorial deadlines in 1927, and *Nature* and the *Comptes Rendus* always reports publication dates. To make entry dates comparable across journals and over time, we assume that editorial deadlines were 14 days before the publication date of the journal.

We calculate average arrival delays as the difference between the arrival date (as measured by the entry stamp) and the publication date and average these delays for each year (1910, 1913, 1917, 1919, 1921, 1923, 1927) and journal.

Because of the way that journals were bound at Heidelberg, entry stamps are only preserved for the first issue of each volume for the *Annalen der Physik* at Heidelberg (see appendix Table E.1, column 4). When we report differences between arrival delays for the *Annalen der Physik* at Harvard and Heidelberg, we only use issue numbers that were available in both libraries.

E.2 Further Details on the ICM Proceedings, 1897-1932

We collect data on the number of delegates at all *International Congresses of Mathematicians* (ICMs) from 1897 until 1932 from historical volumes of the ICM Proceedings, available at http://www.math-union.org/home/. After each congress, the local organizers edited one or more volumes of ICM Proceedings summarizing the main information regarding the conference. The historical ICM Proceedings were written in the official language of the host country, e.g., German for the 1904 ICM held in Heidelberg and Italian for the 1908 ICM held in Rome. Among other information, the volumes report the full list of participants at each congress. This list contains the professional address of each participant. From this address, we obtain the number of delegates by countries reported in Table II.

E.3 Further Details on the Solvay Conferences in Physics

We collect data on the participants of every *Solvay Conference* in Physics from 1911 (first edition) until 1930 from Mehra (1975). For each conference, Mehra (1975) reports a historic picture of the participants during the event with the corresponding names and professional addresses (at the moment of the event). We use this information on the country for Figure II and appendix Table A.2. In some of the historic pictures in Figure II, only a subset of all conference participants appear.

E.4 Further Details on Linking Scientist Censuses with Papers, Citations, and Nobel Prize Nominations

E.4.1 Further Details on the Censuses of University Scientists for 1900 and 1914

As described in the main text, we digitize two historical censuses of all university scientists in the world from the 1900 and 1914 volumes of *Minerva–Handbuch der Gelehrten Welt.* Because the formatting of early volumes of *Minerva* makes the use of Optical Character Recognition software infeasible, all names and specializations are typed in by hand with the help of research assistants. The data list 569 universities in the year 1900 and 973 universities in the year 1914 (appendix Table A.1, panel a). Across all fields, the data contain 24,166 professors in 1900 and 42,226 professors in 1914.[52] A few universities, mostly smaller and less well-known institutions, only reported the number of professors but not their names. The data therefore contain names of 23,917 professors in 1900 and 36,777 professors in 1914 (appendix Table A.1, panel a). In the five scientific fields we study in our analysis, the data contain 10,133 scientists in 1900 and 15,891 scientists in 1914 (appendix Table A.1, panel b).

E.4.2 Further Details on Selection of Journals

From the 263 journals available in the ISI Century of Science database (http://wokinfo.com/products_tools/backfiles/cos/), which covers journals published before WWII, we download all journals apart from journals that mostly publish engineering research (e.g. *Proceedings of the Institute of Radio Engineers*), specialized medicine (e.g. *American Journal of Insanity*), or Geology (e.g. *Soil Science*), resulting in 184 journals. The *Web of Science* does not include papers for publication years before 1930 for 23 of these journals, mostly because the journals were founded after 1930. This results in 161 journals with valid data between 1905 and 1930. Finally, one journal (Zoologiska Bidrag fran Uppsala) published only 40 papers between 1905 and 1930 and none was published by the university scientists in our sample.

E.4.3 Further Details on Obtaining Full information on all References

The publication and citation data from the Web of Science have the following structure:

Table E.2: Example Data Structure Web of Science

Citing paper	**References**
Citing paper 1 (full information)	reference 1 (partial information)
Citing paper 1 (full information)	reference 2 (partial information)
Citing paper 1 (full information)	reference 3 (partial information)
Citing paper 1 (full information)	reference 4 (partial information)
Citing paper 2 (full information)	reference 1 (partial information)
Citing paper 2 (full information)	reference 2 (partial information)
Citing paper 2 (full information)	reference 3 (partial information)
⋮	⋮

As indicated in the table presented above, the Web of Science reports only partial information for each reference. Instead of including the full reference with all authors and complete journal infor-

[52] We use the term professor to refer to individuals who were the equivalent of assistant professors, associate professors, or full professors. We thank Clément de Chaisemartin, Henrik Kleven, Katrine Loken, Ioana Marinescu, Sharun Mukand, and Matti Sarvimäki for help with classifying university positions in various countries.

mation, each reference lists at most five items: the first author, the publication year of the reference, an abbreviation of the journal name, the volume of the journal, and the first page of the article.

We obtain complete references, including a full list of referenced scientists, their affiliations (if available), and the total number of citations received by the reference, by merging the full information from all papers in our data to the references. To improve the quality of this match, we first correct spelling inconsistencies in the abbreviated name of the referenced journal.[53]

References abbreviate journal names, such as the *Proceedings of the National Academy of Sciences of the United States of America* (PNAS) in various ways, such as "p natl acad sci usa," "p nat ac us," and with dozens of other abbreviations. We manually standardize around 2,000 different ways of spelling the abbreviated names of referenced journals.

E.4.4 Further Details on Assigning Countries to Citing Papers and References

As described in the main text, we assign countries to scientists and references in a three step hierarchical process. First, we use the country information from the affiliation reported in papers that list affiliations. Second, we use the country information from the two scientist censuses, first using the 1914 data and then the 1900 data. Third, we expand the country information for scientists with identical names within the corresponding cited or citing journal.

In the first step of our country assignment, we use the affiliation reported in papers that list affiliations.

In the second step of our country assignment, we match the country information of the scientist censuses to the Web of Science data. To maximize the quality of this match, we match on the last name, the initials, and the research field in a two-step process. First, we match on last name, all initials, and research field; second, we match previously unmatched papers on the basis of last name, first initial, and research field. Some scientists reported up to three research fields in the scientist census data, e.g. biology and medicine. Some journals also published research from multiple fields. We map scientist fields into journal fields as follows:

[53] References may not merge during this step for two reasons: first, the reference was not published in one of the 160 journals in our data and, second, some items in the reference are misspelled. In our sample, we obtain full information on 62 percent of recent references. Because we need to measure the country and quality of references for our analysis, we focus on papers with full reference information.

Table E.3: Mapping Journal Fields to Scientist Fields

Journal field	Journal Example	Scientists with the following fields are matched to papers in respective journals
Medicine	Lancet	Medicine
Medicine/Biology	Pflugers Archiv fur die Gesamte Physiologie des Menschen und der Tiere	Medicine, Biology
Medicine/Biology/Chemistry	Archiv fur Experimentelle Pathologie und Pharmakologie	Medicine, Biology, Chemistry
Medicine/Chemistry	Journal of Pharmacology And Experimental Therapeutics	Medicine, Chemistry
Biology	Annals of Applied Biology	Biology
Biochemistry	Biochemical Journal	Biology, Chemistry
Chemistry	Angewandte Chemie	Chemistry
Physical Chemistry	Journal of Physical Chemistry	Chemistry, Physics
Physics	Physical Review	Physics
Mathematical Physics	Sitzungsberichte der Preussischen Akademie Physikalisch-Mathematische Klasse	Physics, Mathematics
Mathematics	Acta Mathematica	Mathematics
General Science	Nature	Medicine, Biology, Chemistry, Physics, Mathematics

Scientists with a single research field in the scientist census data, e.g. physics, are matched with all articles in journals that publish some research in physics, i.e. physics, general science, mathematical physics, and physical chemistry. Scientists with multiple fields in the scientist census data, e.g. mathematics and physics, are matched to all articles that publish some research in mathematics or physics.

The match with the scientist census data is done hierarchically. First, we match scientists from the Web of Science data to the scientists from the 1914 census, as 1914 is in the middle of our sample period. Scientists who do not merge with the 1914 census are matched to the 1900 census.

In the third step of our country assignment, we expand the country information for scientists with identical names within the corresponding citing or cited journal.

E.4.5 Further Details on the Nobel Nomination Data

As described in the main text, we collect data on all nominees for the Nobel Prize from Nobelprize.org (2014). The data contain 993 individuals who were nominated for a Nobel Prize for the first time between 1905 and 1945. To identify winners and the period when winners worked on their Nobel prize winning research, we merge these data with the data on Nobel Prize winners from Jones and Weinberg (2011).

We determine the main nomination field (physics, chemistry, or medicine/physiology) of each nominee by counting the number of nominations in each field. The main nomination field is the field for which a candidate obtained most nominations. E.g. if a scientist received five nominations in physics and one in chemistry, we defined his main nomination field as physics.

We then merge the nominees to all papers in our list of 160 journals from the Web of Science for the publication years 1900 to 1940. To improve the quality of this match, and to reduce the probability of false positives, we only match publications in journal fields that corresponded to likely publication patterns of scientists in certain fields. E.g. we only match publications in physics, general science, mathematical physics, physical chemistry, and chemistry to individuals who received the majority of their nominations for the physics prize.

For six nominees, the last name and the initials of the first name were not unique, e.g. "Paul Weiss" and "Pierre Weiss" were both nominated for a prize between 1905 and 1945. To minimize the probability of false positives, we do not match these individuals if they work in the same field. Three of the six, however, worked in different fields, e.g. "Paul Weiss" was predominately nominated for the medicine prize and "Pierre Weiss" was predominately nominated for the physics prize. We match these three scientists to a very strict definition of journal fields. E.g. we only match them to physics journals (but not general science and other journals if they were physicists).

E.4.6 Further Details on Novel Scientific Words and their Application in U.S. Patents

We measure how the interruption of international knowledge flows impacted the introduction of novel scientific words in the titles of academic papers. We define a novel word as a word that did not appear in any paper title before and that appears in at least one paper afterwards. To identify novel words, we use the full set of 462,871 papers that were published in any of the 160 top journals between 1900 until 1940, independently of whether the paper was published by a scientist in our sample of university scientists. To avoid that common words are included in this novel word count, we preemptively remove 10,000 frequent English words as well as all numbers from the data.

The word list is based on the 10,000 most frequent words in the English books found on Project Gutenberg on 16th April 2006. This word list is available at https://en.wiktionary.org/wiki/Wiktionary:Frequency_lists#English. As the Project Gutenberg word list does neither contain all verb forms (i.e. conjugations) nor necessarily singular and plural forms of nouns (e.g. it only contains scatter but not scatters), we also remove the equivalent forms of verbs and nouns. The results are robust to excluding only 5,000 or all 36,662 frequent words reported from Project Gutenberg as of April, 16, 2006. This allows us to count the number of novel words which appear in the titles of the papers published by any of the university scientists in our sample between 1905 and 1930. If a novel word first appears in more than one paper in one year, we count this word for all papers in that year.

We also measure whether the novel scientific words were applied in patents. We obtain digitalized versions of U.S. patents for grant years 1920 to 1979 from the web page of the United States Patent Office (https://www.uspto.gov/). The data are in plain text format and were created by optical character recognition (OCR). As a result the texts may contain recognition errors.

We first split the text file into individual patents using the string "*** BRS DOCUMENT BOUNDARY ***" as a marker for a new patent record. We extract the grant date of the patent using the marker "AISD." We extract the patent text between the markers "United States Patent Office" and "AISD." In total, we use over 65 different regular expressions to account for possible misspellings of "United States Patent Office." The final data contain over 2.5 million patents with a total of more than 7.5 billion words. For 17,754 patents (0.7 percent of all patents) the OCR quality does not allow us to extract the relevant information and we drop them from the sample.

We use these data to count the number of times a novel scientific word appeared in patents that were granted between year $t + 15$ and $t + 30$, where t corresponds to the publication year of the scientific paper that introduced a novel word. As an example, for a paper that introduced a novel word in 1905, we search patents granted between 1920 and 1935.

E.5 Further Details on War Intensity Data

Data on war intensity come from Mougel 2011, *1914-1918 online: International Encyclopedia of the First World War*, and *Wikipedia.*

We create an indicator for whether a country experienced any combat by checking the battlefronts of WWI combining information from *Wikipedia:*

1. https://en.wikipedia.org/wiki/Western_Front_(World_War_I)
2. https://en.wikipedia.org/wiki/Italian_Front_(World_War_I)
3. https://en.wikipedia.org/wiki/Romania_during_World_War_I
4. https://en.wikipedia.org/wiki/History_of_Poland_during_World_War_I
5. https://en.wikipedia.org/wiki/History_of_South_Africa_(1910%E2%80%9348)
6. https://en.wikipedia.org/wiki/Eastern_Front_(World_War_I)#/media/File:Map_Treaty_of_Brest-Litovsk-er jpg
7. https://en.wikipedia.org/wiki/Balkans_Campaign_(World_War_I)
8. https://en.wikipedia.org/wiki/Middle_Eastern_theatre_of_World_War_I,

and *1914-1918 online International Encyclopedia of the First World War:*

9. http://encyclopedia.1914-1918-online.net/article/greece
10. http://encyclopedia.1914-1918-online.net/article/warfare_1914-1918_new_zealand.

Data on total WWI-deaths and civilian deaths come from Mougel (2011), who compiles deaths by country for project REPERES. Mougel (2011) lists total deaths per capita and the total number of civilian deaths. We convert civilian deaths into civilian deaths per capita by dividing them by the total population. Mougel (2011) reports deaths by country in the borders of 1914. In our analysis, we separately analyze Ireland and the the rest of the United Kingdom; and Austria and Hungary. We obtain country-specific measures of WWI-deaths for Ireland, Austria, and Hungary from Wikipedia (https://en.wikipedia.org/wiki/World_War_I_casualties).

E.6 Further Details on Obituaries

We collect data on obituaries from *Science*, *Nature*, *Physikalische Zeitschrift, Sitzungsberichte der Preussischen Akademie der Wissenschaften, and Kürschners Deutscher Gelehrtenkalend*er.

For *Science,* we record deaths announcements as reported in the "Notes and News" and "Obituary" sections between 1905 and 1930. We download the full text of all the "Notes and News" sections as PDFs from *JSTOR* and search for key phrases such as "deaths are announced," "regret to learn of the death" or "regret also to record the death" to identify death announcements. Research assistants then record death annoucements from the surrounding text. Additionally, we hand collect information on death announcements as reported in the "Obituary" sections of *Science*.

For *Nature,* we record all death announcements from the "News" and "Obituary" sections published between 1905 and 1930. Research assistants individually checked the titles in all "News" sections and manually record death announcements. In the "Obituary" sections the title and the first paragraph contain the information on the deceased scientist that we record manually. Additional obituaries are introduced by the paragraph "We regret to announce the following deaths."

For *Physikalische Zeitschrift* we obtain the full text from *hathitrust.org* for the years 1905 to 1922, and from print versions of the journal for the years 1923 to 1930. In both cases we manually record death announcements from the "Personalien" sections.

For *Sitzungsberichte der Preussischen Akademie der Wissenschaften*, we download the full text and search for paragraphs containing the phrase "durch den Tod" and "starb" for the year 1905 to 1922. Research assistants then record death announcements from these paragraphs.

For *Kürschners Deutscher Gelehrtenkalender* we manually digitize death announcements from the list of deceased scientists published in three volumes of the *Gelehrtenkalender* (1926, 1928/29, and 1931) .

In all cases we collect the name, the date of death and, if available, the specialization of the deceased scientist. If no specific death date is given, we use the year of the publication as an upper bound for the year of death.

Between 1905 and 1930, the five sources published 6,507 obituaries, reporting on 5,435 unique individuals. We hand-check obituaries to harmonize spellings of names and year of death across sources. In the next step, we remove obituaries on clergymen and military personnel. Finally, we retain the 3,084 obituaries that report deaths of scientists in the five fields of our main analysis (mathematics, physics, chemistry, biology, and medicine). Of these, 1,856 can be merged to the scientists in our sample, indicating that the scientist passed away between 1905 and 1930.